PB82-231168

Combustion Modification Controls for Residential and Commercial Heating Systems Volume I: Environmental Assessment

Acurex Corp.
Mountain View, CA

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Jul 81

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

EPA-600/7-81-123a

July 1981

Research and Development

PB82-231168

COMBUSTION MODIFICATION CONTROLS FOR RESIDENTIAL AND COMMERCIAL HEATING SYSTEMS

Volume I. Environmental Assessment

Prepared for

Office of Air Quality Planning and Standards

Prepared by

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/7-81-123a

2.

3. RECIPIENT'S ACCESSION NO.
PB82-231168

4. TITLE AND SUBTITLE Combustion Modification Controls for Residential and Commercial Heating Systems: Volume I. Environmental Assessment

5. REPORT DATE
July 1981

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Acurex/Energy and Environmental Division
485 Clyde Avenue
Mountain View, California 94042

10. PROGRAM ELEMENT NO.
EHE624A

11. CONTRACT/GRANT NO.
68-02-2160

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development
Industrial Environmental Research Laboratory
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED
Task Final; 6/78-9/79

14. SPONSORING AGENCY CODE
EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Joshua S. Bowen, Mail Drop 65, 919/541-2470.

16. ABSTRACT
The report gives an environmental assessment of combustion modification techniques for residential and commercial heating systems, with respect to NOx control reduction effectiveness, operational impact, thermal efficiency impact, control costs, and effect on emissions of pollutants other than NOx. Major equipment types and design trends are reviewed, although emissions and control data for commercial systems are very sparse. Natural gas and distillate oil are the principal fuels. NOx, CO, unburned hydrocarbons, and (for oil firing) particulate are the primary pollutants. For gas-fired residential systems, high radiative heat transfer burners have been developed, which lower NOx emissions by about 80% without increasing emissions of combustibles. For oil-fired residential systems, several new burner designs, including integrated burner/furnace systems, have been developed, which lower NOx by 20-85% and generally decrease CO, UHC, and particulate emissions. Commercial application of these systems is very limited. Since the control techniques generally increase thermal efficiency, the additional initial investment cost can often be recouped in a year. Field test data of a commercial, oil-fired, low-NOx residential system indicate that the system poses less of an environmental hazard than older conventional systems.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Heating	Stationary Sources	13H
Combustion Control	Residential Systems	21B
Nitrogen Oxides	Commercial Systems	07B
Natural Gas	Combustion Modification	21D
Fuel Oil	Environmental Assessment	14B
Assessments		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	177
	20. SECURITY CLASS (This page)	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

RESEARCH REPORTING SERIES

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EPA-600/7-81-123a
July 1981

COMBUSTION MODIFICATION CONTROLS FOR RESIDENTIAL AND COMMERCIAL HEATING SYSTEMS:
VOLUME I. ENVIRONMENTAL ASSESSMENT

By

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Contract 68-02-2160
Program Element EHE 624A

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OFFICE OF RESEARCH AND DEVELOPMENT
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This Final Report was furnished to the U.S. Environmental Protection Agency by Acurex Corporation, Energy & Environmental Division, Mountain View, California 94042, in partial fulfillment of Contract No. 68-02-2160. The opinions, findings, and conclusions expressed are those of the authors and not necessarily those of the Environmental Protection Agency or of cooperating agencies. Mention of company or product names is not to be considered as an endorsement by the Environmental Protection Agency.

PREFACE

This is one in a series of five process engineering reports documented in the "Environmental Assessment of Stationary Source NO_x Combustion Modification Technologies" (NO_x EA). Specifically, this report documents the environmental assessment of residential and commercial heating systems with primary emphasis on NO_x combustion controls for residential warm air furnaces. The NO_x EA, a 36-month program which began in July 1976, is sponsored by the Combustion Research Branch of the Industrial and Environmental Research Laboratory of EPA (IERL-RTP). The program has two main objectives: (1) to identify the multimedia environmental impact of stationary combustion sources and NO_x combustion modification controls applied to these sources, and (2) to identify the most cost-effective, environmentally sound NO_x combustion modification controls for attaining and maintaining current and projected NO_2 air quality standards to the year 2000.

The NO_x EA is assessing the following combination of process parameters and environmental impacts:

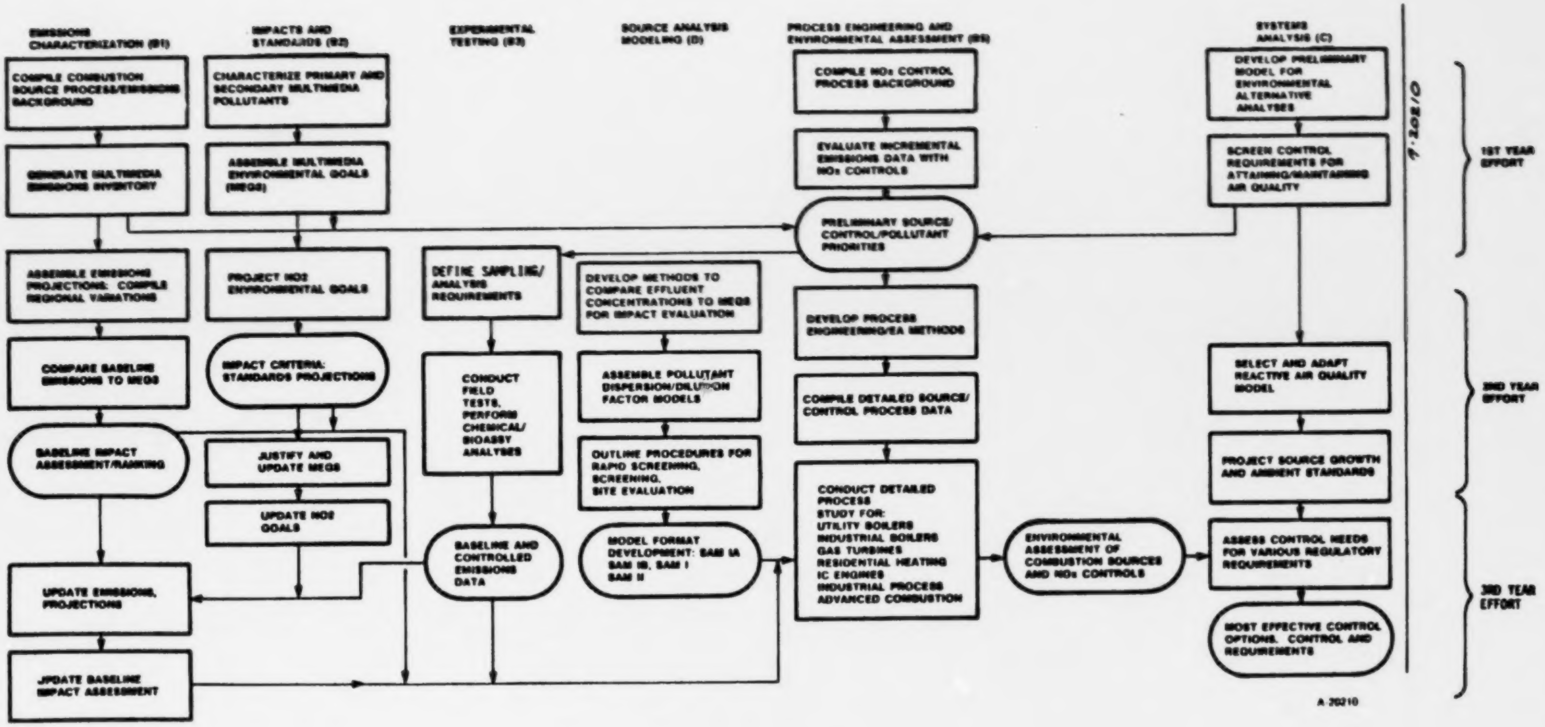
- Major fuel combustion stationary NO_x sources: utility boilers, industrial boilers, gas turbines, internal combustion (IC) engines, and commmercial and residential warm air furnaces. Other sources (including mobile and noncombustion) will be considered only to the extent that they are needed to determine the NO_x contribution from stationary combustion sources.
- Conventional and alternate gaseous, liquid and solid fuels
- Combustion modification NO_x controls with potential for implementation to the year 2000; other controls (flue gas cleaning, mobile controls) will be considered only to estimate the future need for combustion modifications

- Source effluent streams potentially affected by NO_x controls
- Primary and secondary gaseous, liquid and solid pollutants potentially affected by NO_x controls
- Pollutant impacts on human health and terrestrial or aquatic ecology

To achieve the objectives discussed above, the NO_x EA program approach is structured as shown schematically in Figure P-1. The two major tasks are: Environmental Assessment and Process Engineering (Task B5), and Systems Analysis (Task C). Each of these tasks is designed to achieve one of the overall objectives of the NO_x EA program cited earlier. In Task B5, of which this report is a part, the environmental, economic, and operational impacts of specific source/control combinations are evaluated. On the basis of this assessment, the incremental multimedia impacts from the use of combustion modification NO_x controls will be identified and ranked. Systems analysis in turn uses the results of Task B5 to identify and rank the most effective source/control combinations to comply, on a local basis, with the current NO_2 air quality standards and projected NO_2 related standards.

As shown in Figure P-1, the key tasks supporting Tasks B5 and C are Baseline Emissions Characterization (Task B1), Evaluation of Emission Impacts and Standards (Task B2), and Experimental Testing (Task B3). The arrows in Figure P-1 show the sequence of subtasks and the major interactions among the tasks. The oval symbols identify the major outputs of each task. The subtasks under each main task are shown on the figure from the top to the bottom of the page in roughly the same order in which they will be carried out.

As indicated above, this report is a part of the Process Engineering and Environmental Assessment Task. The goal of this task is to generate process evaluations and environmental assessments for specific source/control combinations. These studies will be done in order of descending priority. In the first year of the NO_x EA, all the sources and controls involved in current and planned NO_x control implementation programs were investigated. The "Preliminary Environmental Assessment of Combustion Modification Techniques" (Reference P-1) documented this effort and established a priority ranking based on source emission impact and


EMISSIONS CHARACTERIZATION (B1)
IMPACTS AND STANDARDS (B2)
EXPERIMENTAL TESTING (B3)
SOURCE ANALYSIS MODELING (D)
PROCESS ENGINEERING AND ENVIRONMENTAL ASSESSMENT (B5)
SYSTEMS ANALYSIS (C)
COMPILE COMBUSTION SOURCE PROCESS/EMISSIONS BACKGROUND
GENERATE MULTIMEDIA EMISSIONS INVENTORY
ASSEMBLE EMISSIONS PROJECTIONS: COMPILE REGIONAL VARIATIONS
COMPARE BASELINE EMISSIONS TO MEGS
BASELINE IMPACT ASSESSMENT/RANKING
UPDATE EMISSIONS, PROJECTIONS
UPDATE BASELINE IMPACT ASSESSMENT
CHARACTERIZE PRIMARY AND SECONDARY MULTIMEDIA POLLUTANTS
ASSEMBLE MULTIMEDIA ENVIRONMENTAL GOALS (MEGS)
PROJECT NO2 ENVIRONMENTAL GOALS
IMPACT CRITERIA: STANDARDS PROJECTIONS
JUSTIFY AND UPDATE MEGS
UPDATE NO2 GOALS
DEFINE SAMPLING/ ANALYSIS REQUIREMENTS
CONDUCT FIELD TESTS, PERFORM CHEMICAL/ BIOASSY ANALYSES
BASELINE AND CONTROLLED EMISSIONS DATA
DEVELOP METHODS TO COMPARE EFFLUENT CONCENTRATIONS TO MEGS FOR IMPACT EVALUATION
ASSEMBLE POLLUTANT DISPERSION/DILUTION FACTOR MODELS
OUTLINE PROCEDURES FOR RAPID SCREENING, SCREENING, SITE EVALUATION
MODEL FORMAT DEVELOPMENT: SAM IA SAM IB, SAM I SAM II
COMPILE NOx CONTROL PROCESS BACKGROUND
EVALUATE INCREMENTAL EMISSIONS DATA WITH NOx CONTROLS
PRELIMINARY SOURCE/ CONTROL/POLLUTANT PRIORITIES
DEVELOP PROCESS ENGINEERING/EA METHODS
COMPILE DETAILED SOURCE/ CONTROL PROCESS DATA
CONDUCT DETAILED PROCESS STUDY FOR: UTILITY BOILERS INDUSTRIAL BOILERS GAS TURBINES RESIDENTIAL HEATING IC ENGINES INDUSTRIAL PROCESS ADVANCED COMBUSTION
ENVIRONMENTAL ASSESSMENT OF COMBUSTION SOURCES AND NOx CONTROLS
DEVELOP PRELIMINARY MODEL FOR ENVIRONMENTAL ALTERNATIVE ANALYSES
SCREEN CONTROL REQUIREMENTS FOR ATTAINING/MAINTAINING AIR QUALITY
SELECT AND ADAPT REACTIVE AIR QUALITY MODEL
PROJECT SOURCE GROWTH AND AMBIENT STANDARDS
ASSESS CONTROL NEEDS FOR VARIOUS REGULATORY REQUIREMENTS
MOST EFFECTIVE CONTROL OPTIONS, CONTROL AND REQUIREMENTS
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1ST YEAR EFFORT
2ND YEAR EFFORT
3RD YEAR EFFORT
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Figure P-1. NO_x EA approach.

potential for effective NO_x control, to be used in the current ongoing detailed evaluation.

This report presents the assessment of combustion modification NO_x controls for the last source category to be treated, residential and commercial heating systems. Other environmental assessment reports documented are:

- Environmental Assessment of Utility Boiler Combustion Modification NO_x Controls (Reference P-2)
- Environmental Assessment of Industrial Boiler Combustion Modification NO_x Controls (Reference P-3)
- Environmental Assessment of Combustion Modification Controls for Stationary Gas Turbines (Reference P-4)
- Environmental Assessment of Combustion Modification Controls for Stationary Internal Combustion Engines (Reference P-5)

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P-5. Lips, H. I., *et al.*, "Environmental Assessment of Combustion Modification Controls for Stationary Internal Combustion Engines," EPA-600/7-81-127, July 1981.

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SECTION 1
EXECUTIVE SUMMARY

With more NO_x controls being implemented in the field and expanded control development anticipated for the future, there is currently a need to: (1) ensure that the current and emerging control techniques are technically and environmentally sound and compatible with efficient and economical operation of systems to which they are applied, and (2) ensure that the scope and timing of new control development programs are adequate to allow stationary sources of NO_x to comply with potential air quality standards. The residential and commercial heating system environmental assessment helps to address these needs by evaluating the operational, economic and environmental impacts from applying combustion modification NO_x controls.

Residential warm air furnaces, the major source category dealt with in this report, are the fifth largest contributors of man-made NO_x emissions from stationary sources in the U.S. -- constituting about 2 percent of annual nationwide emissions. It is projected that their contribution will remain significant through the year 2000 (Reference 1-1). Given this background and their potential for NO_x control, residential and commercial heating systems were specified as a major category to be studied under the NO_x EA program.

1.1 OVERVIEW OF RESIDENTIAL AND COMMERCIAL HEATING SYSTEMS

The major domestic fuel combustion sources are central warm air furnaces, room or direct heaters, residential hot water heaters, and steam and hot water hydronic boilers for space and water heating. Minor sources include stoves and fireplaces; these consume a relatively insignificant quantity of fuel compared to other space heating equipment.

The primary fuels for residential heating are natural gas and distillate oils (no. 1, kerosene, or no. 2 distillate). These fuels combined account for nearly 90 percent of all fuel burned for domestic heating. Liquified petroleum gas, LPG (butane or propane), coal and wood are also used, although in relatively small quantities. In 1976 LPG-fired equipment account for about 6 percent of domestic heating equipment while coal- and wood-fired units account for only 2 percent of the total equipment population. Built-in electric residential heating systems have become increasingly popular as domestic supply of clean fuels dwindles and fuel costs increase. Electrical heaters in 1976 accounted for nearly 14 percent of residential heating equipment.

The primary fuels and equipment used for domestic heating show significant regional variation. For example, the Northeast regions depend primarily on oil-fired steam or hot water units while in all other regions, natural gas-fired central warm air furnaces are the primary equipment type for domestic space heating.

Combustion equipment in most residential heating systems is similar. For natural gas-fired equipment the single port upshot or the tubular multiport burners are the most common burner types. Natural gas-fired warm air furnaces, room heaters, or hot water heaters often use a pilot flame to ignite the burner automatically. Distillate oil-fired residential heating systems generally use high pressure atomizing gun type burners. Nearly all new oil-fired burners use the flame retention burner head which promotes more efficient combustion.

Commercial heating systems can be divided into three general categories: warm air unit heaters or space heaters, warm air furnaces or duct heaters, and hot water or steam systems. The combustion system of commercial warm air unit or space heaters and duct heaters is generally similar to residential equipment, although there are a few unique gas-fired designs. Warm air units and duct heaters are either direct or indirect fired. Direct fired heaters use only clean gaseous fuels. These units exhaust the combustion products directly into the heated space. Indirect fired heaters use either gas or oil fuels and are vented to the outdoors. These units, except for their larger capacity, are generally similar to residential central warm air furnaces. Information on equipment population and emissions from commercial space heaters is limited.

Hot water and steam systems in the commercial size capacity, here defined in the range of 0.12 to 2.9 MW ((0.4 to 10) x 10^6 Btu/hr) heat input capacity, include cast iron hydronic boilers and small firetube and watertube boilers used in both the commercial and industrial sectors. Cast iron hydronic boilers are also used in residential as well as commercial applications. These units, which are common in the Northeastern and Northcentral regions of the U.S., are primarily either gas- or distillate oil-fired. Firetube and small watertube boilers used for heating of large commercial plants and buildings are similar to the smaller industrial boilers used to generate process steam. These boilers are generally fired with gas, oil or less frequently stoker coal, and account for about 25 percent of the installed capacity of steam and hot water boilers with heat input capacity less then 2.9 MW (10 x 10^6 Btu/hr).

1.2 EMISSIONS AND FUELS

Because natural gas and distillate oil are the principal fuels used in domestic and commercial heating systems, air pollutant emissions represent the primary waste stream of environmental concern. Coal- and wood-fired furnaces and stoves, however, also produce solid ash waste streams. Although increasing in popularity due to the scarcity and high cost of clean fuels, residential wood- and coal-fired systems account for only 2 percent of all domestic heaters. Thus nationally, solid waste streams from residential heating pose only a minor environmental concern but are potentially significant when considered on a local or regional basis. Commercial coal-fired watertube and firetube stokers are also the source of solid waste streams. These units, which account for about 15 percent of the firetube and watertube population, could increase in popularity with economic and political incentives for increased use of domestic coal.

Flue gas stream composition from residential heating equipment depends highly on the type of fuel burned, burner type, combustor geometry, combustor material and operating characteristics. Natural gas-fired equipment emits NO_x, carbon monoxide (CO) and unburned hydrocarbons (UHC). When distillate oil is used, particulate (smoke) and small quantities of SO_x are also emitted. NO_x emissions are generally highest and CO, UHC and smoke are lowest when the heater operates at design (tuned) and steady state conditions. SO_2 emissions are a function of the sulfur content of the oil. SO_2 control is primarily achieved by using low sulfur oil.

NO_x is one of the primary pollutants of concern with residential gas- and oil-fired heaters. It is emitted in significant quantities, is deleterious to human respiratory functions and acts as a key precursor to photochemical smog. Carbon monoxide, UHC and smoke made up of carbon particles or soot are products of incomplete combustion. These pollutants are emitted in the largest quantity during ignition, and warm up and shut off periods of a residential furnace heating cycle. Because domestic heaters operate in a cyclic mode combustible emissions due to on-off transients account for the majority of the total yearly emissions. Control techniques for reducing combustible emissions often concentrate on reducing the heater cycling frequency.

Table 1-1 summarizes 1977 emissions for stationary combustion sources with heat input less than 2.9 MW (10×10^6 Btu/hr). These sources include primarily residential and commercial heating systems as well as small industrial boilers (Reference 1-2). Residential and commercial heating systems contribute 56 and 28 percent respectively of the total NO_x from these sources. These emissions are seasonal with nearly all the total annual output occurring in the cold winter months; during that period the impact of residential and commercial heating on ground level ambient NO_2 concentration in urban areas can be significant (References 1-3, 1-4).

1.3 STATUS OF ENVIRONMENTAL PROTECTION ALTERNATIVES

Emission control technology for residential and commercial equipment is typically adapted to the specific fuel and burner type. Because NO_x emissions from either gas or distillate oil combustion are primarily due to thermal NO_x, control techniques are aimed at controlling temperature or oxygen availability in the high temperature flame region. Tables 1-2 and 1-3 summarize NO_x control alternatives for residential heaters firing natural gas and distillate oil respectively. These controls have been developed primarily for warm air furnaces; however, the advanced burner and combustor redesign technology presented

TABLE 1-1. ESTIMATED 1977 AIR POLLUTANT EMISSIONS FROM STATIONARY FUEL COMBUSTION SOURCES WITH HEAT CAPACITY LESS THAN 2.9 MW (10 x 10^6 Btu/hr)[a]

Sector	Equipment	Fuel	Total Capacity MW (10^6 Btu/hr)	Fuel[b] Consumption EJ (Quads)	Air Pollutant Emissions Gg (10^3 tons)				
					NO_x	CO	HC	Particulates	SO_x
Residential[c]	Warm air central furnaces	Natural gas	--	1.876[c] (1.979)	65.7 (72.5)	19.0 (20.9)	6.40 (7.10)	7.50 (8.27)	0.49 (0.54)
		Distillate oil	--	1.354[c] (1.428)	33.8 (37.3)	33.8 (37.3)	6.40 (7.06)	10.3 (11.4)	146 (161)
	Warm air space heaters	Natural gas	--	0.57[c] (0.60)	19.9 (21.9)	5.7 (6.3)	1.94 (2.14)	2.30 (2.54)	0.15 (0.17)
		Distillate oil	--	0.42[c] (0.44)	10.5 (11.6)	10.5 (11.6)	1.97 (2.17)	3.20 (3.53)	45.4 (50.1)
Residential and Commercial	Miscellaneous combustion	Natural gas	--	1.524[c] (1.608)	53.3 (58.8)	15.2 (16.8)	5.20 (5.73)	6.10 (6.73)	0.40 (0.44)
		Distillate oil	--	0.926[c] (0.977)	27.4 (30.2)	27.4 (30.2)	5.15 (5.68)	8.33 (9.19)	118.4 (130.6)
	Steam and hot water heaters	Natural gas	--	2.1[c] (2.2)	82.8 (91.3)	17.8 (19.6)	4.76 (5.25)	16.6 (18.3)	0.62 0.68
		Distillate oil	--	1.4[c] (1.5)	77.9 (85.9)	41.7 (46.0)	13.4 (14.8)	10.6 (11.7)	150.2 (165.6)
		Residual oil	--	0.11[c] (0.12)	17.5 (19.3)	1.64 (1.81)	2.74 (3.02)	9.09 (10.0)	52.6 (58.0)
		Coal	--	0.043[c] (0.045)	7.1 (7.8)	7.53 (8.30)	2.12 (2.34)	150.2 (165.6)	30.7 (33.8)

[a] Based on data from References 1-1, 1-2, and 1-5.

[b] EJ = 10^{18} Joules = 0.948 Quads = 0.948 x 10^{15} Btu

[c] Fuel consumption for residential units was obtained from Department of Energy (Reference 1-5).

TABLE 1-1. (Concluded)

Sector	Equipment	Fuel	Total Capacity MW (10^6 Btu/hr)	Fuel[b] Consumption EJ (Quads)	Air Pollutant Emissions Gg (10^3 tons)				
					NO_x	CO	HC	Particulates	SO_x
Commercial and Industrial	Cast iron boilers	Natural gas	143,520 (489,495)	1.8 (1.9)	91.7 (101.1)	35.3 (38.9)	4.06 (4.48)	6.88 (7.59)	0.53 (0.58)
		Distillate oil	33,730 (115,041)	0.35 (0.37)	23.7 (26.1)	0.56 (0.61)	3.34 (3.68)	4.18 (4.61)	37.6 (41.5)
		Residual oil	53,790 (183,456)	0.47 (0.50)	84.6 (93.3)	0.66 (0.73)	11.8 (13.8)	13.2 (14.6)	225.6 (248.8)
		Coal	31,590 (107,742)	0.097 (1.0)	14.6 (16.1)	21.3 (23.5)	5.53 (6.10)	314.3 (346.6)	110.6 (122.0)
	Watertube boilers	Natural gas	5,770 (19,679)	0.053 (0.056)	3.16 (3.5)	1.06 (1.17)	0.18 (0.20)	0.05 (0.05)	0.02 (0.02)
		Distillate oil	4,490 (15,313)	0.021 (0.023)	1.18 (1.3)	0.06 (0.07)	0.01 (0.01)	0.18 (0.20)	3.27 (3.61)
		Residual oil	5,240 (17,872)	0.015 (0.016)	2.38 (2.6)	0.02 (0.02)	0.07 (0.08)	0.42 (0.46)	6.70 (7.39)
		Coal	1,900 (6,480)	0.012 (0.013)	3.0 (3.3)	0.91 (1.00)	0.19 (0.21)	23.5 (25.9)	16.0 (17.6)
	Firetube boilers	Natural gas	79,090 (269,748)	1.358 (1.433)	31.0 (34.2)	15.2 (16.8)	1.75 (1.93)	3.02 (3.33)	0.23 (0.25)
		Distillate oil	31,530 (107,538)	0.37 (0.39)	12.8 (14.1)	0.34 (0.38)	2.05 (2.26)	2.57 (2.83)	18.7 (20.6)
		Residual oil	48,200 (164,393)	0.354 (0.374)	30.7 (33.9)	0.29 (0.32)	5.12 (5.65)	5.73 (6.32)	92.1 (101.61)
		Coal	14,420 (49,181)	0.11 (0.116)	14.1 (15.6)	5.40 (5.95)	3.40 (3.75)	130.0 (143.4)	91.8 (101.2)
TOTAL	All equipment	All fuels	--	15.22 (16.97)	708.8 (781.6)	261.4 (288.3)	87.6 (96.6)	728.3 (803.1)	1,148.1 (1,266.0)

TABLE 1-2. PERFORMANCE SUMMARY OF LOW-NO_x CONTROL EQUIPMENT FOR NATURAL GAS-FIRED RESIDENTIAL HEATERS

Control	Average Operating Excess Air (percent)	Cyclic Pollutant Emissions ng/J Heat Input			Steady State Efficiency (percent)	Cycle Efficiency (percent)	1978 Installed Control Cost	Comments
		NO_x[a]	CO	UHC[b]				
Conventional Units	40-120	28-45	8.6-25	3.3-33	70	60-65	c	Emission factors from References 1-6 and 1-7. Costs include installation
Radiant Screens	40-120	15-18	6.4	NA	75	70	NA	Emissions of CO and HC can increase significantly if screen is not placed properly or deforms
Secondary Air Baffles	60-80	22	14	NA	NA	NA	NA	Requires careful installation. Best suited for single port upshot burners
Surface Combustion Burner	10	7.5	5.5-9.6	NA	NA	NA	$100-$200	Not commercially available. Still under development
Amana (HTM)	NA	7.7	26	NA	85	80	$100-$300 over conventional furnace	Commercially available design. Spark ignited thus requires no pilot
Modulating Furnace	NA	25	NA	NA	75	70	$50-$250 over conventional furnace	Furnace is essentially derated. Thus it requires longer operation to deliver a given heat load
Pulse Combustor	NA	10-20	NA	NA	95	95	$300-$600	Currently being investigated by AGAL. Efficiencies correspond to condensing systems.
Catalytic Combustor	NA	<5	NA	NA	90	85	$100-$250	Still at the R&D stage. Efficiencies correspond to condensing systems.

[a] Sum of NO + NO_2 reported as NO_2
[b] Unburned hydrocarbons calculated as methane (CH_4)
[c] Typical costs of uncontrolled unit $500-$800
NA = not available

TABLE 1-3. PERFORMANCE SUMMARY OF LOW-NO_x CONTROL EQUIPMENT FOR DISTILLATE OIL-FIRED RESIDENTIAL HEATERS

Control	Average Operating Excess air (percent)	Cyclic Pollutant Emissions ng/J Heat Input					Steady State Efficiency (percent)	Cycle Efficiency (percent)	1978 Installed Control Cost	Comments
		NO_x	CO	UHC[b]	Smoke Number	Particulate				
Conventional Units	50-85	37-85	15-30	3.0-9.0	3.2	7.6-30	75	65-70	c	Range in NO_x emissions is for residential systems not equipped with flame retention burners (References 1-4 and 1-8). Emissions for other pollutants are averages reported in References 1-7 and 1-8.
Flame Retention Burner Head	20-40	26-88	11-22	0.2-1.8	2.0	NA	80-83 also depends on heat exchanger	NA	\$52[d]	If a new burner is needed as well as a burner head, the total cost would be \$385.
Controlled Mixing Burner Head by EPA/ Rocketdyne	10-50	34	13	0.7-1.0	<1.0	NA	80 also depends on heat exchanger	NA	\$43[d]	Cost of mass produced burner head only about \$1.50. Combustible emissions are relatively low because hot firebox was used.
Integrated Furnace System by EPA/ Rocketdyne	20-30	19	20	1.2	<1.0	NA	84	74	\$250 over conventional furnace	Uses optimized burner head. For new furnace installation only. Combustible emissions are higher than with burner head because of quenching in in air cooled firebox. Recent cost estimate.
Blueray "blue flame" Burner/Furnace System	20	10	4.5-7.5	1.5-2.5	zero	NA	84	74	\$100 over conventional furnace	New installation only. Furnace is commercially available. Recent cost estimate.
M.A.N. Burner	10-15	10-25	<30	NA	<1.0	NA	85	NA	NA	Both for-retrofit or new installations. Not yet commercially available in U.S. Commercialization expected in 1980.

[a] Sum of NO and NO_2 reported as NO_2
[b] Unburned hydrocarbons calculated as Methane
[c] Typical costs of uncontrolled unit \$650-\$1,000
[d] Original costs reported for years other than 1978 were corrected for inflation using Gross National Product (GNP) implicit price inflators (Reference 1-9)
NA -- Not available

in these tables could possibly be applied also to other domestic heating equipment as well as some larger commercial installations.

For residential gas-fired heaters, the American Gas Association Laboratories (AGAL) developed radiant screens and secondary air baffles capable of average NO_x reductions of 58 and 20 percent respectively. However, these controls may find little application because of installation and performance problems highlighted by the Gas Appliance Manufacturer Association (GAMA). Two advanced NO_x control alternatives are the Bratko surface combustor and the Amana Heat Transfer Module (HTM). In these concepts, the radiation from the combustion zone maintains a lower temperature of the combustion products and thus lower NO_x production while maintaining good efficiency and low CO levels. NO_x emissions from both the Bratko and Amana burners are approximately 80 percent below levels of conventional warm air furnaces. Between the two, the Amana is the only commercially available unit and its cost to the consumer is generally $100 to $300 above that of a conventional furnace.

The modulating furnace system produces a cooler flame by altering the burner firing rate to respond to heating costs instead of cycling on and off. NO_x reductions of about 40 percent have been reported. AGAL is currently investigating pulse combustion for residential heating using a condensing exhaust gas system. Preliminary NO_x emissions have been reported in the 19 to 20 ng/J range. Commercialization of the pulse combustor residential heating system is expected in 1981. Catalysts promoting combustion of fuel at low temperature offer potential for very low NO_x emissions while maintaining good combustion efficiency. Research groups and trade organizations are investigating the commercial feasibility of catalytic combustion for residential warm air and hot water systems burning natural gas. Performance and emission data for these systems have not yet been published; however, NO_x emissions are expected to be very low.

Residential oil-fired heaters are forced draft fired and therefore more readily modified for reduced emissions and increased efficiencies than natural draft gas-fired heaters. Early work involved the development of the flame retention oil burner. These units produce lower CO, UHC and smoke emissions and operate on excess air lower than previous conventional oil burner designs. In some particular designs the flame retention devices also lower NO_x emissions by 20 to 40 percent. Furthermore, they stay tuned longer and thus maintain low combustible emission levels (Reference 1-6). These units are now the primary residential oil burners sold.

As part of their combustion research program, the EPA has supported low-NO_x high efficiency residential burner development since 1971. Under one program, Rocketdyne developed a controlled mixing burner head for retrofit and new applications on domestic heaters. It was estimated that widespread application of the relatively inexpensive burner head device would be effective in reducing NO_x by 20 percent and increase efficiency by 5 percent on the average for each retrofitted furnace. Recently the burner has been integrated with an "optimum"* low emission high efficiency warm air furnace. NO_x emissions have been reduced by 65 to 70 percent and steady state efficiencies have been increased by 10 percent over those of conventional designs. The EPA program emphasized the necessity to match the firebox, burner and heat exchanger design to achieve low-NO_x emissions while also maintaining low levels of CO, UHC and smoke.

Both the Blueray "blue flame" and the M.A.N. burners use aerodynamic flue gas recirculation to achieve a blue flame with distillate fuel oil. These burners thus achieve reduced flame temperature, dilution of the oxygen concentration in the near-burner zone and rapid vaporization of the fuel prior to ignition. These conditions result in low NO_x emissions on the order of 15 to 40 ppm corrected at zero percent excess air, representing NO_x reductions of 50 to 80 percent. Theoretically, these burner concepts could be scaled up to larger commercial sizes. The Blueray furnace system is currently the only commercially available low-NO_x system in the U.S. for oil-fired residential use.

Control techniques aimed at reducing seasonal pollutant emissions from residential heating systems through improved fuel economy and general reduced equipment usage are listed in Table 1-4. Replacement of wornout furnaces, tuning and changes in thermostat anticipator setting represent the most effective control techniques with overall combustible emission reductions ranging from 16 to 65 percent for CO, 3 to 87 percent for UHC, 59 percent for smoke, and 17 to 33 percent for particulates. Installation of delayed action solenoid valves and reduced firing capacity through minor modification or installation of a new flame retention burner are effective in reducing excessive smoke emissions during furnace start-up and shut-down periods. Reported average smoke reductions range from 24 to 82 percent. In general, all these techniques result in fuel savings sometimes as high as 39 percent in addition to lowering combustible emissions.

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*Terminology used by Rocketdyne to characterize the final design capable of achieving program goals.

Application of control technology to commercial heating equipment is very limited. Theoretically, the flame quenching and surface combustion concepts investigated for gas-fired residential equipment could also apply to commercial heaters burning natural gas. Similarly, low-NO_x burner designs for distillate oil firing or optimum air-fuel mixing concepts could possibly be scaled up to the larger commercial equipment.

NO_x control technology from the gas- and oil-fired industrial boiler source category include low-NO_x burners, staged combustion, flue gas recirculation, load reduction and low excess air operation. These techniques could possibly be applicable to commercial size boilers of similar design. Low-NO_x burners represent the most attractive control alternative for this boiler size category. Some U.S. companies are currently working on new burner design concepts, primarily for oil-fired boilers. Most of these efforts, however, have been oriented toward industrial (2.9 to 73.3 MW heat input) size boilers.

1.4 ENVIRONMENTAL AND COST IMPACTS

As a part of the NO_x EA program, a Blueray low-NO_x high-efficiency residential furnace was tested in the field to quantify the environmental impact of low-NO_x residential systems. Results from these tests were then compared with those from another program in which seven conventional oil-fired residential heaters (five warm air and two hot water) using high pressure atomizing burners were field tested.

TABLE 1-4. PERFORMANCE SUMMARY OF CONTROLS FOR REDUCTION OF SEASONAL COMBUSTIBLE, SMOKE AND PARTICULATE EMISSIONS FROM OIL-FIRED RESIDENTIAL HEATERS

Control	Percent Reduction (Average)				Percent Improvement in Fuel Saving	1978 Installed Control Cost	Comments
	CO	UHC	Smoke	Particulates			
Replacement of worn-out units	(65)	(87)	NC^{a}	(17)	NA^{b}	\$650-\$1000^{c} for new warm air furnaces	Nine percent of the existing residential heaters were found in need of replacement. Recent cost estimates.
Tuning and scheduled seasonal maintenance	(16)	(3.0)	(59)	(7.0)	1.7 percent average efficiency increase	\$38-\$60^{c}	Tuning results is an increase in efficiency for some units and a decrease in efficiency for others.
Delayed action solenoid valves	NA	NA	60-90 (80)	NA	NA	\$43^{c}	Smoke emission reduction primarily during start-up and shut-down.
Reduced excessive firing capacity with conventional burner	(14)	NA	10-38 (24)	(3.7)	5.6-2.5 (14)	\$52^{c}	Installation of flame retention head cone plus modifications to reduce firing capacity by about 36 percent.
Reduced excessive firing capacity with new retention burner	(14)	NA	80-85 (82)	(3.7)	14-39 (30)	\$385^{c}	Installation of new lower capacity burner with flame retention head retention head. Firing capacity reduced by 43 percent.
Installation of positive chimney dampers	2.0-19 (11)	NA	NA	2.2-17 (10)	3-9	\$200^{c}	Large variation in pollutant sion reduction due to changes in furnace cycle frequency. Recent cost estimate.
Change in thermostat anticipator setting	41-45 (43)	NA	NA	31-33 (33)	0-2	Minimal	Very effective for residential units with high cyclic frequency.
Overnight thermostat cut-back (3-5K)	9.1-27 (17)	NA	NA	12-24 (15)	7-15	Minimal	Cost does not take into account improved home insulation which might be necessary with thermostat cut-back.

[a] NC = No change

[b] NA = Not available

[c] Costs for material and labor are typical of New England area. Original costs reported for years other than 1978 were corrected for inflation using Gross National Product (GNP) implicit price inflators (Reference 1-9)

In general, the Blueray unit showed decreases of criteria and noncriteria pollutants when compared with conventional heaters. For cyclic operation, particulate, SO_3, and trace elements were 70 to 80 percent lower for the Blueray low-NO_x furnace. However, total organic emissions from the Blueray unit were about five times higher than the average emissions from the seven conventional heaters. Switching from continuous to cyclic operation, NO_x emissions from the Blueray furnace decreased because of lower NO_x during transient furnace operation. Particulates and trace element emissions generally remained unchanged. Emissions of Fe, Ni and possibly Cr, Mn, and Mo decreased significantly when switched to cyclic operations. However, trace element results need verification since sample contamination from steel metal surfaces was suspected.

A rapid screening of potentially hazardous emissions from the Blueray furnace and conventional oil-fired heaters was performed using the Source Analysis Model (SAM IA) (Reference 1-10). For the purpose of screening pollutant emissions data to identify species requiring further study, a Discharge Severity (DS) is calculated using SAM IA procedures. DS is defined as the ratio of a pollutant species discharge concentration to that species' Discharge Multimedia Environmental Goal (DMEG). The DMEG value represents a threshold, or "allowable" discharge concentration of a pollutant, above which adverse health or ecological effects may occur. When DS exceeds unity, more refined chemical analysis may be required to quantity specific compounds present.

Table 1-5 lists discharge severities for those species with DS greater than 0.1. The DS for NO_x was significantly lower for the Blueray furnace, decreasing from a value of about 5 for conventional units (representing potential environmental hazard), to less than 1.0 for the low-NO_x unit. Of the trace elements, Cr and Ni emissions present the greatest potential hazard; in all cases their DS is a sizeable fraction of total stream DS. However, measured levels of these metals may be an artifact of the stream sampling methodology. The flue gas sampling trains in both the conventional furnace test program and the NO_x EA contained many stainless steel components. Thus, some of the reported Cr and Ni

TABLE 1-5. FLUE GAS DISCHARGE SEVERITIES GREATER THAN 0.1 FOR THE BLUERAY FURNACE AND CONVENTIONAL OIL-FIRED HEATERS

Pollutant	Blueray Furnace (Reference 1-11)		Conventional Furnace (Reference 1-12)
	Continuous Operation	Cyclic Operation	Cyclic Operation
NO_x	0.86	0.60	4.7[a]
SO_2	1.6	2.1	6.3[a]
SO_3	0.15	0.77	4.5
CO	0.17	1.1	0.3[a]
Arsenic (As)	0.23	0.27	0.60
Calcium (Cd)	0.17	0.11	0.85
Chromium (Cr)	85	5.5	22
Cobalt (Co)	0.14	0.11	ND[b]
Copper (Cu)	0.075	0.055	0.60
Iron (Fe)	0.42	0.046	0.011
Lead (Pb)	0.14	0.14	0.21
Nickel (Ni)	4.5	0.73	15
Thallium (Th)	0.37	0.41	ND[b]
Amines	NF[c]	NF[c]	1.6
Carboxylic acid	0.20	2.3	NF[c]
Total Stream DS	95.7	15.5	59.0

[a] Pollutant not measured in test program, DS calculated from AP-42 emission factors: NO_x, 55 ng/J; SO_2, 106 ng/J; CO, 15 ng/J

[b] ND: Species not analyzed for

[c] NF: None found

could have come from the sampling train itself rather than being a significant component of the flue gas.

For both types of units SO_2 emissions were flagged and emissions of certain organic categories had DS values greater than 1. For the conventional units amines were flagged as being of potential concern; for the Blueray unit carboxylic acids would be of potential concern under cyclic operation. The DS for NO_x exceeds 1 for conventional units, but is less than 1 for the low-NO_x Blueray unit under both continuous and cyclic operations.

In summary, flue gas stream Total Discharge Severity (TDS) for typical conventional units appears to fall between the TDS for the low-NO_x unit under cyclic (normal) operation and that for both the low-NO_x unit under continuous operation. If Cr and Ni are removed from the TDS calculations, adjusted TDSs of 32.7, 5.3, and 18.3 result for the conventional, Blueray continuous, and Blueray cyclic data, respectively. Thus, if measured Cr and Ni indeed comes from the sampling train, then the low NO_x unit's TDS under both cyclic and continuous operation is lower than that of the conventional units. This suggests that using the Blueray design to control NO_x from oil-fired heating units is environmentally sound.

Table 1-6 summarizes estimated cost data for the most effective NO_x control alternatives for residential heating systems. As indicated, retrofit of the controlled mixing burner head (EPA/Rocketdyne) for residential oil-fired warm air furnaces represents the most cost-effective alternative to achieve a NO_x emission level of about 45 ng/J of useful heat. Surface combustion, pulse combustor and catalytic burner for gas-fired units and the Rocketdyne developed technologies for oil-fuel units are not commercially available. The payback periods listed in the table are estimates based on the time required to recover the money spent for the initial investment of installing NO_x control equipment. Since all of these control alternatives bring about an increase in thermal efficiency, and thus fuel savings, the initial investment cost is often recouped over a one year or less time period.

TABLE 1-6. COST IMPACT OF NO_x CONTROL ALTERNATIVES

Control	Fuel	Achievable NO_x Level ng/J Useful Heat	1978 Incremental Investment Cost	Cost Effectiveness \$/ng/J[a]	Payback Period Based on Annual Fuel Bill of \$500
Amana (HTM) Furnace	Natural Gas	12 (390 ng/m^3 fuel)	\$100-\$300 over cost of conventional furnace	1.7-5.2	1-3 years
Modulating Furnace	Natural Gas	35 (920 ng/m^3 fuel)	\$50-\$250 over cost of conventional furnace	1.4-7.0	1-3.8 years
Surface Combustion Burner (Infrared Bratko type)	Natural Gas	12 (380 ng/m^3 gas)	\$100-\$200 over cost of conventional furnace/heater	1.7-3.4	3.5-8.0
Pulse Combustion Burner[b]	Natural Gas	21 (683 ng/m^3 gas)	\$300-\$600 over cost of conventional furnace/heater	6.1-12.2	1.7-3.5
Catalytic Combustion Burner[b]	Natural Gas	Estimate 5 (163 ng/m^3 gas)	\$150-\$250 over cost of conventional furnace/heater	2.3-3.9	1.4-2.3
Flame Retention Burner Head	Distillate Oil	50 (1.8 g/kg fuel)	\$52 -- retrofit including installation	2.6	Less than 1 year
Flame Retention Burner	Distillate Oil	50 (1.8 g/kg fuel)	\$385 -- retrofit of reduced capacity burner	12.8	3.5 years
EPA/Rocketdyne Burner Head	Distillate Oil	45 (1.6 g/kg fuel)	\$43 -- retrofit including installation	1.3	Less than 1 year
EPA/Rocketdyne Furnace	Distillate Oil	29 (0.7 g/kg/fuel)	\$250 over cost of conventional furnace	4.2	2.5 years
Blueray Furnace	Distillate Oil	20 (0.7 g/kg fuel)	\$100 over cost of conventional furnace	1.7	1 year

[a] Based on uncontrolled NO_x emissions of 70 ng/J heat output for natural gas-fired heaters and 80 ng/J heat output for distillate oil-fired heaters. Cost-effectveness is based of the differential investment cost of the control.

[b] Based on installation of a condensing system where seasonal efficiencies can be as high as 95 percent.

1.5 DATA NEEDS AND RECOMMENDATIONS

A modest amount of information has been gathered on emissions from residential space heating equipment. In addition, control alternatives for NO_x and combustible pollutants have also been investigated. Some low-NO_x and high efficiency furnace designs are commercially available, while other equally effective designs are either at final demonstration stages or await commercialization. Performance tests on these improved heating designs are being gathered through EPA sponsored field and laboratory programs. These and other test programs will aid in further documenting the performance, reliability of these advanced controls and quantifying their impact on other pollutant emissions.

Cost data on NO_x control alternatives for residential heating systems were generally sparse and imprecise. This lack of definitive cost data prevented a detailed economic impact assessment of widespread implementation of control alternatives. As advanced controls become available, future EA programs should quantify the cost impact of NO_x control implementation to achieve specific level of controls.

Investigative efforts on NO_x control alternatives for commercial size steam and hot water boilers burning gas or oil is also scarce. While it can be speculated that some boiler designs lend themselves to NO_x control techniques developed for industrial size boilers, little experimental data exist to confirm this. Low-NO_x burner technology for heat input capacities in the size range of 0.1 to 2.9 MW (0.4 to 10 x 10^6 Btu/hr) shows promise based on advanced burner technology developed for both residential units on the small side and industrial units on the larger side.

NO_x control technology for solid-fuel-fired residential and commercial equipment, is also very limited. Past and on-going test programs have mainly dealt with quantifying the pollutant levels and identifying equipment operating parameters and fuel characteristics which have some impact on these levels. Primary pollutants of interest for this category of equipment have been particulate and smoke emissions as well as levels of unburned hydrocarbons, toxic elements and polycyclic organic matter (POM). The simplicity of the solid-fuel-fired equipment, whether coal- or wood-fired, often does not permit extensive modifications of existing equipment or operating procedures to reduce NO_x levels. Investigative efforts in this area should continue to determine potential NO_x control technology applicable to new unit design while still concentrating on reducing the impact of other criteria and noncriteria pollutant emissions.

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SECTION 2
INTRODUCTION

This report assesses the operational, economic, and environmental impacts from applying combustion modification NO_x controls to residential and commercial combustion equipment with heat input capacity less than 2.9 MW (10×10^6 Btu/hr). With more NO_x controls being implemented in the field and expanded control development anticipated for the future, there is currently a need to: (1) ensure that the current and emerging control techniques are technically and environmentally sound, and compatible with efficient and economical operation of systems to which they are applied, and (2) ensure that the scope and timing of new control development programs are adequate to allow stationary sources of NO_x to comply with potential air quality standards. The NO_x EA program addresses these needs by (1) identifying the incremental multimedia environmental impacts of combustion modification controls, and (2) identifying the most cost-effective source/control combinations to achieve ambient NO_2 standards.

2.1 BACKGROUND

Since the 1970 Clean Air Act Amendments, techniques have been developed and implemented that reduce NO_x emissions by a moderate amount (30 to 60 percent) for a variety of stationary source/fuel combinations. In 1971, EPA set NSPS for large steam generators burning gas, oil, and coal (except lignite). Recently, more stringent standards for utility boilers burning bituminous and subbituminous coals have been promulgated, along with new standards for lignite fired utility boilers. In addition, NSPS have been proposed for stationary gas turbines reciprocating internal combustion engines and are under study for industrial steam generators. Local standards also have been set, primarily for new and existing large steam generators and gas turbines, as parts of State Implementation Plans in several areas with NO_x problems.

Because of the relaxation of mobile standards, coupled with the continuing growth rate of stationary sources, NO_x control for stationary sources has become more important for maintaining air quality. Thus more stringent controls than current and impending NSPS provide will be required. To meet these standards the preferred approach is to control new sources by using low-NO_x redesigns.

2.2 ROLE OF RESIDENTIAL AND COMMERCIAL HEATING SYSTEMS

This source category includes warm air furnaces and hot water heaters for home heating, and small commercial hot water or steam boilers for plant heating and air conditioning. Home heating equipment consume the largest quantity of fuel within this source category. In 1977, domestic space and water heaters alone consumed about 8 EJ* or approximately 20 percent of the total U.S. energy used by stationary combustion sources (Reference 2-1). Commercial boilers with heat input capacity less than 2.9 MW (10×10^6 Btu/hr) consumed approximately an additional 4.15 EJ, or about 10 percent of total U.S. fuel consumption for stationary combustion sources.

Residential combustion equipment warm air furnaces, steam and hot water heaters and warm air space heaters (combined) is the fifth largest contributor of NO_x emissions in the U.S. Figure 2-1 shows that warm air central furnaces are responsible for 14 percent of NO_x emissions from all sources with heat input capacity less than 2.9 MW (10×10^6 Btu/hr) or about 0.9 percent of total NO_x; steam and hot water heaters contributed 26.1 percent or 1.8 percent of total NO_x; while warm air space heaters contributed another 4.3 percent, or 0.3 percent of total NO_x (updated from Reference 2-3). Steam and hot water boilers (firetubes, watertubes, and cast iron) with a capacity less than 2.9 MW (10×10^6 Btu/hr), used in both commercial and industrial sectors, contributed about another 3.0 percent to the total NO_x emissions.

The impact of residential and commercial heating systems on ambient NO_x levels is much more severe than these low percentage points indicate. The seasonal use pattern, low stack heights and wide geographical distribution of residential and commercial heating systems

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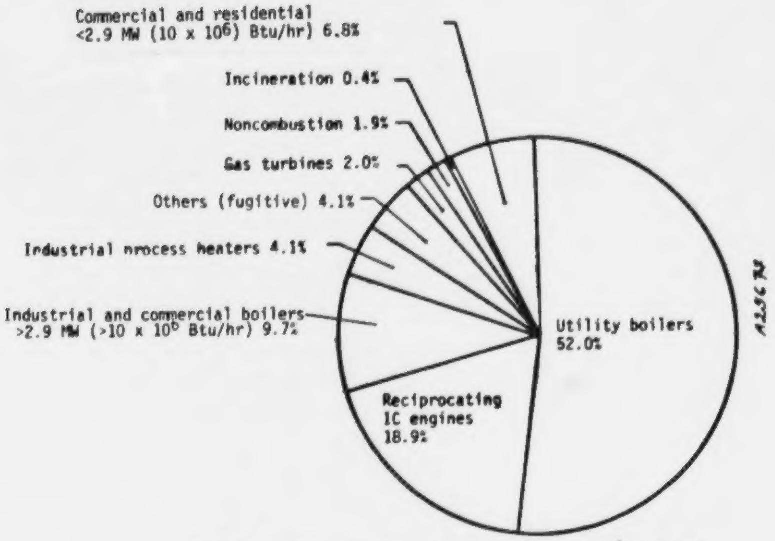
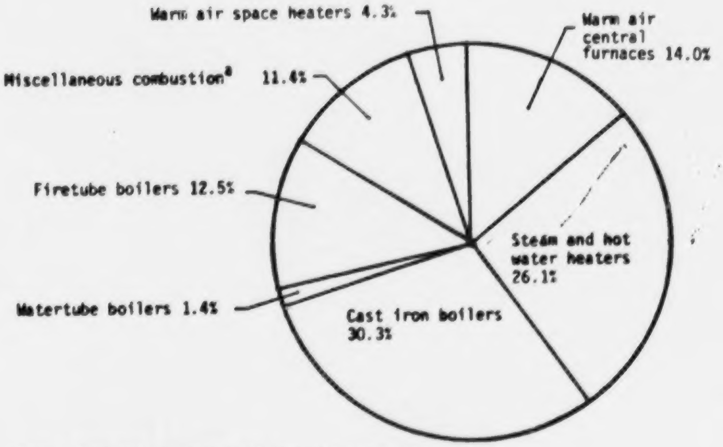
*Does not include about 2 EJ of electricity also used for residential heating.



Total from all sources: 10.5 Tg/yr (11.6×10^6 tons/yr)



Total from all sources with capacity less than 2.9 MW
(10×10^6 Btu/hr): 0.709 Tg/yr (0.781×10^6 tons/yr)

[a]Includes cooling and air conditioning

Figure 2-1. Distribution of stationary anthropogenic NO_x emissions for the year 1977 (controlled NO_x levels) (Reference 2-2).

are often the cause of high NO_2 ambient levels in populated urban areas. the contribution of these sources often exceeds that of other stationary or transportation sources during the "heating season" (References 2-4 and 2-5). With the increasig number of homes and commercial buildings requiring heating and air combustion systems will continue to be a problem unless adequate controls are developed. The problem may be aggravated as fuels such as residual oils or stoker coal which show a propensity for higher NO_x formation, becomes more attractive in the face of shortages and higher prices of natural gas and distillate oils normally used for home and commercial heating.

Given this background and their potential for NO_x control, residential and commercial heating systems were selected as a major source category to be studied under the NO_x EA program. The "Preliminary Environmental Assessment of Combustion Modification Techniques" (Reference 2-5) concluded that modifying combustion process conditions is the most effective and widely used technique for achieving 20 to 70 percent reduction in oxides of nitrogen. Nearly all current NO_x control applications use combustion modifications. Other approaches, such as treating postcombustion flue gas, are generally not considered feasible for application on small residential and commercial heating systems.

2.3 OBJECTIVE OF THIS REPORT

This report evaluates and compares the important environmental and process engineering aspects of available or emerging combustion modification techniques for residential and commercial heating systems with special emphasis on central warm air furnaces. Subobjectives of this evaluation are:

- Evaluate control impact on total multimedia emissions
- Identify the effect of control application on equipment performance and identify potential problem areas
- Estimate the economics of control implementation
- Estimate the limits of control achievable for the significant sources as fuels
- Identify research and development and/or testing needs to optimize combustion modification techniques and to upgrade their assessment

2.4 ORGANIZATION OF THIS REPORT

The components of the environmental assessment reported here are as follows:

- Characterize the source category with regard to equipment, fuels and emissions (Section 3)
- Review pollutant formation mechanisms and relate fuels to their emissions potential (Section 4)
- Evaluate the performance of current and developing NO_x control techniques available for implementation (Section 5)
- Estimate the capital and operating costs, including energy impacts of implementing NO_x control (Section 5)
- Evaluate the environmental impact of NO_x controls through the analysis of incremental emissions (Section 6)
- Assess the total impact of NO_x controls on ambient air, economics, energy and operations and maintenance of the residential equipment, thereby evaluating the effectiveness of current and emerging control technology (Section 6).

With some exceptions due to the nature of the subject treated, the reporting format conforms to the "Environmental Assessment Report" guidelines developed by EPA's Industrial Environmental Research Laboratory for disseminating results of EPA's environmental assessment program.

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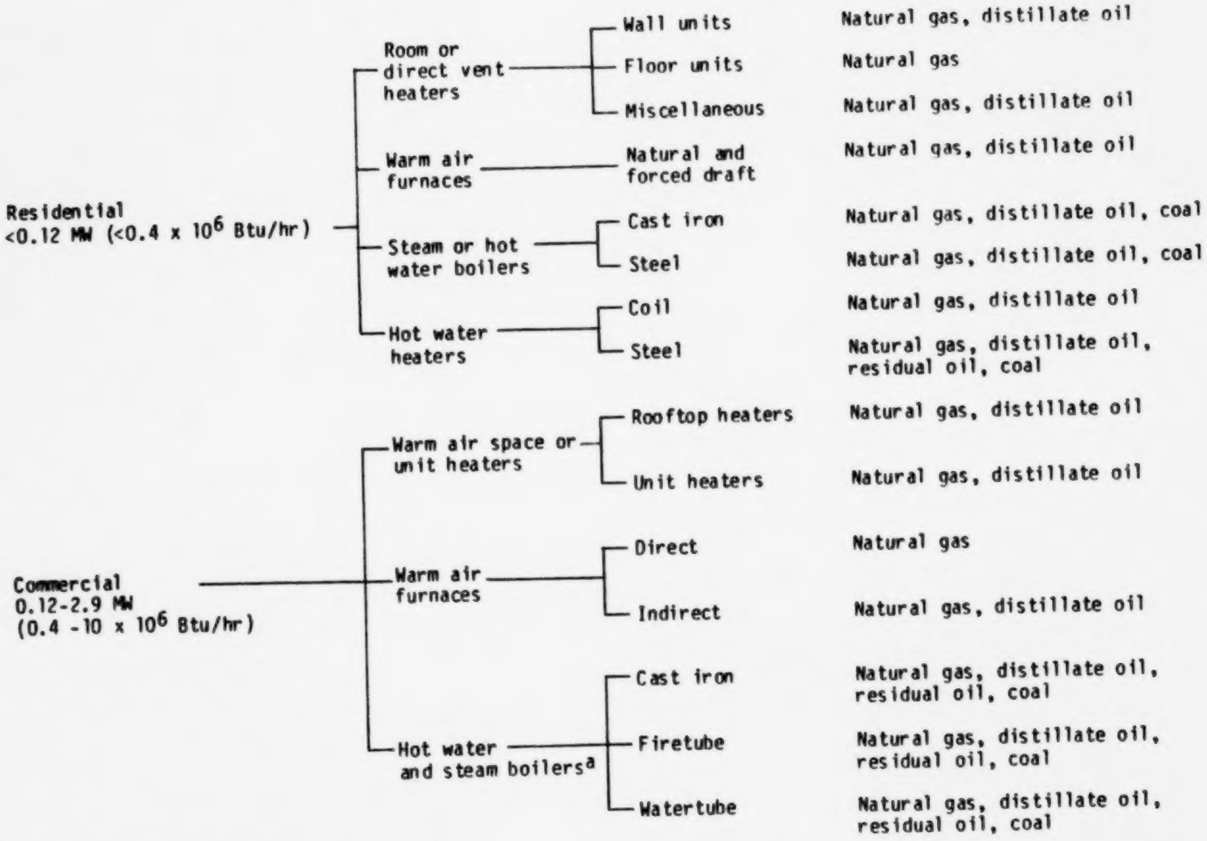
SECTION 3
SOURCE CHARACTERIZATION

This section characterizes space heating combustion sources with heat input capacity less than 2.9 MW (10 x 10^6 Btu/hr). This size category covers steam and hot water systems and warm air furnaces in both the residential and commercial sectors. In addition, it includes process steam or hot water units in the industrial sector with capacity less than 2.9 MW (10 x 10^6 Btu/hr). Equipment types, population and installed capacity, current design practice, and areas of environmental concern are identified and discussed.

3.1 EQUIPMENT TYPES

Figure 3-1 summarizes the types of residential and commercial combustion equipment used for space heating. For this report the distinction between residential and commercial units is arbitrarily set at 0.1 MW (400,000 Btu/hr) heat input capacity, although, warm air furnaces, space heaters, and hot water or steam units below this firing rate are also used in commercial establishments. Units with capacity above 0.1 MW (400,000 Btu/hr) are rarely found in single family residential dwellings. Figure 3-1 indicates that there are four generic equipment types -- (1) room heaters or direct vent heaters used for domestic warm air, (2) space or unit heaters only used for commercial direct heating, (3) warm air furnaces used for both residential and commercial heating, and (4) hot water or steam systems also used for domestic and commercial heating. Warm air room heaters or direct vent heaters are single room heaters which may be mounted in the wall, floor or from the ceiling. Warm air furnaces are central air units delivering warm air to a number of rooms. In many cases, especially in commercial systems the warm air heating system is integral with a central air conditioning system. Space or unit heaters are used solely for commercial heating, exhausting hot combustion products


Residential
<0.12 MW (<0.4 x 10^6 Btu/hr)
Room or direct vent heaters
Wall units
Natural gas, distillate oil
Floor units
Natural gas
Miscellaneous
Natural gas, distillate oil
Warm air furnaces
Natural and forced draft
Natural gas, distillate oil
Steam or hot water boilers
Cast iron
Natural gas, distillate oil, coal
Steel
Natural gas, distillate oil, coal
Hot water heaters
Coil
Natural gas, distillate oil
Steel
Natural gas, distillate oil, residual oil, coal
Commercial
0.12-2.9 MW
(0.4 -10 x 10^6 Btu/hr)
Warm air space or unit heaters
Rooftop heaters
Natural gas, distillate oil
Unit heaters
Natural gas, distillate oil
Warm air furnaces
Direct
Natural gas
Indirect
Natural gas, distillate oil
Hot water and steam boilers^a
Cast iron
Natural gas, distillate oil, residual oil, coal
Firetube
Natural gas, distillate oil, residual oil, coal
Watertube
Natural gas, distillate oil, residual oil, coal

[a] Also found in the industrial sector.

Figure 3-1. Distribution of residential and commercial heating systems.

directly into the space being heated. Finally, hot water or steam systems, may be utilized for either space heating or for process hot water or steam. The following sections present the population distribution of these commercial and residential units by fuel, equipment type, and region.

3.1.1 Residential Units

Table 3-1 lists domestic heating populations based on 1976 U.S. Census data by equipment type and fuel (Reference 3-1). The Census data indicate that central warm air furnaces are the most common residential combustion equipment accounting for nearly 53 percent of the entire population. Natural gas is currently the principle house heating fuel accounting for about 56 percent of total fuel used. Oil and kerosene rank second as sources of energy with about 22 percent, while electricity, which has recently grown in popularity, in 1976 accounted for nearly 14 percent of the total energy used.

Table 3-2 lists the distribution of residential equipment by fuel type for the four U.S. Census Regions. In the Northeast Region, a higher percentage of fuel oil is consumed than other fuels, whereas in all other regions natural gas is the predominant domestic fuel. Equipment distribution also varies regionally (Table 3-3). In the Northeast Region, steam or hot water systems comprise the highest percentage of all residential equipment types. This indicates that, although gas-fired warm air systems dominate nationally, oil-fired hot water or steam units can be significant air pollution contributors on a regional basis.

3.1.2 Commercial Units

With the exception of the hot water or steam boilers below 2.9 MW (10×10^6 Btu/hr) firing capacity, no compilation of user statistics or sales was found for commercial size space heating equipment. However, discussion with manufacturers revealed the following:

- There are both gas-fired and oil-fired unit heaters and warm air furnaces or duct heaters in the commercial size range designated in this report, 0.1 to 2.9 MW (0.4 to 10×10^6 Btu/hr)
- Although there are a few unique gas-fired designs, in general the combustion systems of commercial heating equipment is similar in design to the residential equipment

TABLE 3-1. POPULATION AND RANKING OF DOMESTIC HEATING SYSTEMS BY TYPE (1976) -- 1000 UNITS

Heating Equipment	Natural Gas	Bottled or Liquified Petroleum Gas	Oil or Kerosene	Electricity	Other Fuel	Total
Warm Air Furnace	25,042 (34.1)[a]	1,961 (2.7)	6,729 (9.1)	4,877 (6.6)	179 (0.2)	38,787 (52.7)
Steam or Hot Water	5,308 (7.2)	112 (0.2)	7,987 (10.9)	-- --	192 (0.3)	13,598 (18.5)
Floor, Wall or Pipeless Furnace	5,471 (7.4)	503 (0.7)	422 (0.6)	-- --	22 --	6,417 (8.7)
Room Heater with Flue	2,767 (3.8)	636 (0.9)	1,183 (1.6)	-- --	-- --	4,586 (6.2)
Room Heaters w/o Flue	2,331 (3.2)	938 (1.3)	68 (0.1)	-- --	-- --	3,337 (4.5)
Built-in Electric Units	-- --	-- --	-- --	4,794 (6.5)	-- --	4,794 (6.5)
Others (Fireplaces, Stoves)	300 (0.4)	90 (0.1)	62 (0.1)	479 (0.7)	1,090 (1.5)	2,021 (2.7)
Total	41,219 (56.0)	4,240 (5.8)	16,451 (22.4)	10,150 (13.8)	1,483 (2.0)	73,543 (100)

[a] Percent of total systems given in parenthesis.

TABLE 3-2. REGIONAL DISTRIBUTION OF RESIDENTIAL HEATING EQUIPMENT BY FUEL (1976) -- 1000 UNITS

Fuel	Northeast	Northcentral	South	West	Total
Natural Gas	6,140 (8.4)[a]	13,803 (18.8)	11,449 (15.6)	9,826 (13.4)	41,219 (56.0)
Bottled or Liquified Petroleum Gas	125 (0.2)	1,337 (1.8)	2,367 (3.2)	411 (0.6)	4,240 (5.8)
Oil, or Kerosene	9,161 (12.5)	3,004 (4.1)	3,488 (4.7)	798 (1.1)	16,451 (22.4)
Electricity	846 (1.1)	1,366 (1.9)	5,498 (7.5)	2,441 (3.3)	10,151 (13.8)
Coal, Coke	162 (0.2)	102 (0.1)	193 (0.3)	28 (0.04)	485 (0.7)
Other, incl. Wood	101 (0.1)	105 (0.1)	588 (0.8)	204 (0.3)	988 (1.4)
Total	16,535 (22.5)	19,717 (26.8)	23,583 (32.1)	13,708 (18.6)	73,543 (100)

[a] Percent of total systems given in parenthesis.

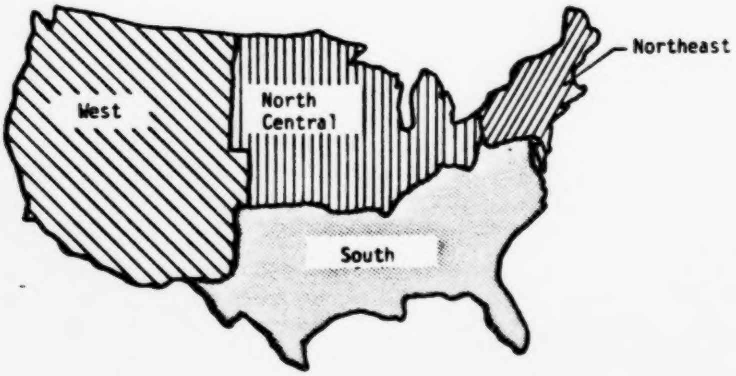
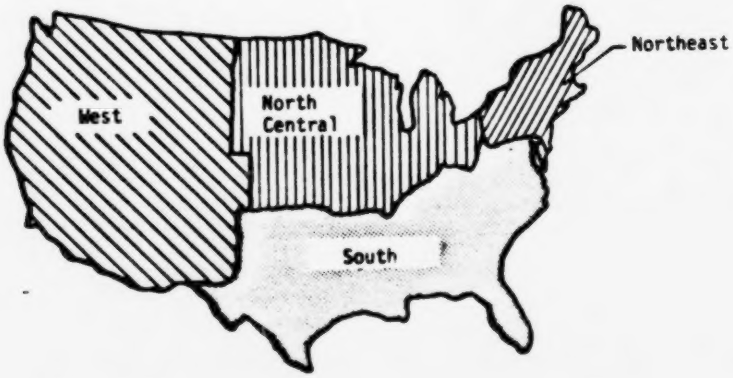


TABLE 3-3. REGIONAL DISTRIBUTION OF RESIDENTIAL HEATING EQUIPMENT BY FUEL (1976) -- 1000 UNITS

Equipment	Northeast	Northcentral	South	West	Total
Warm Air Furnaces	5,984 (8.1)[a]	13,782 (18.7)	11,922 16.2)	7,100 (9.6)	38,788 (52.7)
Steam or Hot Water	8,923 (12.1)	3,068 (4.2)	1,070 (1.5)	538 (0.7)	13,599 (18.5)
Floor, Wall or Pipeless Furnace	174 (0.2)	556 (0.8)	2,365 (3.2)	3,321 (4.5)	6,416 (8.7)
Room Heater with Flue	521 (0.7)	1,220 (1.7)	2,049 (2.8)	796 (1.1)	4,586 (6.2)
Room Heater without Flue	51 (0.1)	52 (0.1)	3,112 (4.2)	122 (0.2)	3,337 (4.5)
Built-in Elect. Units	733 (1.0)	899 (1.2)	1,674 (2.3)	1,488 (2.0)	4,794 (6.5)
Others (Fire-places, Stoves)	148 (0.2)	140 (0.2)	1,390 (1.9)	344 (0.5)	2,022 (2.7)
Total	16,534 (22.5)	19,717 (26.8)	23,582 (32.1)	13,709 (18.6)	73,542 (100)

[a] Percent of total systems given in parenthesis.



- The majority of unit heaters are gas-fired and some of these are "infrared type" burners where surface combustion occurs on a refractory grid
- Warm air heaters are either indirect gas-or-oil-fired similar to the residential units or direct gas-fired where the combustion gases are mixed with the air being heated. This heated air may be used for space heating or for drying.
- Indirect fired warm air heaters are either larger versions of residential design or duct heaters. Duct heaters are usually part of a central air conditioning system or roof top climate control system.
- Rooftop gas-fired central air systems are often utilized in commercial buildings. In more severe climates and high-rise buildings a central boiler, either gas- or oil-fired, is utilized.

Three types of burner systems are commonly used in commercial space heating equipment; these are:

- The atmospheric gas-fired single port, ribbon or multiport burner
- The retention head distillate oil-fired power burner
- The direct gas-fired duct burner

The first two designs are similar to those used for residential systems. These burner systems will be discussed with regard to their pollution impact and control potential in the following sections of this report.

Steam and hot water units with heat input capacity below 2.9 MW (10×10^6 Btu/hr) can be found in both the commercial as well as the industrial sector. These units can be divided into three general equipment types -- watertubes, firetubes, and cast iron boilers. A recent population distribution of these commercial size boilers has been published by Devitt, et al., (Reference 3-2). Tables 3-4 and 3-5 list respectively the 1977 commercial and industrial population and installed capacity for the various types of boilers within this size category.

In the commercial sector (Table 3-4), cast iron boilers account for over 90 percent of all installed steam or hot water units. Nearly 66 percent of these units have heat input less than 0.1 MW (400,000 Btu/hr). Firetube boilers are the second most numerous boiler type accounting for

TABLE 3-4. POPULATION OF BOILERS WITH < 2.9 MW (10 x 10^6 Btu/hr) HEAT INPUT CAPACITY IN USE IN COMMERCIAL SECTOR -- 1977 NUMBER OF UNITS (INSTALLED CAPACITY MW)

Equipment Type	Size Range MW (10^6 Btu)	Stoker Coal	Residual Oil[a]	Distillate Oil[a]	Natural Gas[a]	Total
Watertube	≤0.1 (0.4)	--	--	--	--	--
	0.1-0.4 (0.4-1.5)	392 (110)	399 (140)	1,552 (550)	893 (310)	3,236 (1,110)
	0.4-2.9 (1.5-10)	630 (955)	772 (1,160)	1,183 (1,380)	723 (985)	3,308 (4,480)
Watertube Total	≤0.1-2.9 0.4-10)	1,022 (1,065)	1,171 (1,300)	2,735 (1,930)	1,616 (1,295)	6,544 (5,590)
Firetube	≤0.1 (0.4)	--	--	--	--	--
	0.1-0.4 (0.4-1.5)	13,459 (3,940)	15,731 (4,610)	16,001 (4,690)	30,889 (9,050)	76,080 (22,290)
	0.4-2.9 (1.5-10)	2,866 (4,830)	5,163 (8,310)	5,636 (9,070)	6,715 (10,920)	20,380 (33,130)
Firetube Total	<0.1-2.9 (0.4-10)	16,325 (8,770)	20,894 (12,920)	21,637 (13,760)	37,604 (19,970)	96,460 (55,420)
Cast Iron	≤0.1 (0.4)	90,630 (4,810)	162,855 (12,010)	102,266 (7,530)	421,033 (30,970)	776,784 (55,320)
	0.1-0.4 (0.4-1.5)	37,408 (9,840)	57,291 (12,860)	35,983 (8,090)	175,055 (40,260)	305,737 (71,050)
	0.4-2.9 (1.5-10)	15,826 (10,610)	19,428 (18,140)	12,196 (11,370)	51,221 (43,570)	98,671 (83,690)
Cast Iron Total	<0.1-2.9 (0.4-10)	143,864 (25,260)	239,574 (43,010)	150,445 (26,990)	647,309 (114,800)	1,181,192 (210,060)
All Equipment Types	<0.1-2.9 (0.4-10)	161,211 (35,095)	261,639 (57,230)	174,817 (42,680)	686,529 (136,065)	1,284,196 (271,070)

[a] A number of boilers have dual gas/oil firing capability. Units are listed here by the primary fuel burned.

TABLE 3-5. POPULATION OF BOILERS WITH <2.9 MW (10 x 10^6 Btu/hr) HEAT INPUT CAPACITY IN USE IN THE INDUSTRIAL SECTOR -- 1977 NUMBER OF UNITS (INSTALLED CAPACITY MW)

Equipment Type	Size Range MW (10^6 Btu)	Stoker Coal	Residual Oil[a]	Distillate Oil[a]	Natural Gas[a]	Total
Watertube	≤0.1 (0.4)	--	--	--	--	--
	0.1-0.4 (0.4-1.5)	168 (50)	774 (270)	1,376 (480)	1,521 (540)	3,839 (1,340)
	0.4-2.9 (1.5-10)	515 (785)	2,443 (3,670)	1,775 (2,080)	2,893 (3,935)	7,626 (10,470)
Watertube Total	<0.1-2.9 (0 4-1.0)	683 (835)	3,217 (3,940)	3,151 (2,560)	4,414 (4,475)	11,465 (11,810)
Firetube	≤0.1 (0.4)	--	--	--	--	--
	0.1-0.4 (0.4-1.5)	5,768 (1,690)	30,536 (8,960)	14,190 (4,160)	52,594 (15,420)	103,088 (30,230)
	0.4-2.9 (1.5-10)	2,344 (3,956)	16,348 (26,320)	8,453 (13,610)	26,862 (43,700)	54,007 (87,590)
Firetube Total	<0.1-2.9 (0.4-10)	8,112 (5,650)	46,884 (35,280)	22,643 (17,770)	79,456 (59,120)	157,095 (117,820)
Cast Iron	≤0.1 (0.4)	22,657 (1,200)	40,714 (3,020)	25,567 (1,880)	105,258 (7,740)	194,196 (13,840)
	0.1-0.4 (0.4-1.5)	9,352 (2,460)	14,323 (3,220)	8,996 (2,020)	43,764 (10,080)	76,435 (17,780)
	0.4-2.9 (1.5-10)	3,956 (2,670)	4,857 (4,540)	3,049 (2,840)	12,805 (10,900)	24,667 (20,950)
Cast Iron Total	≤0.1-2.9 (0.4-10)	35,965 (6,330)	59,894 (10,780)	37,612 (6,740)	161,827 (28,720)	295,298 (52,570)
All Equipment Types	≤0.1-2.9 (0.4-10)	44,760 (12,815)	109,995 (50,000)	63,406 (27,070)	245,697 (92,315)	463,858 (182,200)

[a] A number of boilers have dual gas/oil firing capability. Units are listed here by the primary fuel burned.

7.3 percent of all commercial units below 2.9 MW (10 x 10^6 Btu/hr) heat input capacity. In the industrial sector (Table 3-5), cast iron boilers account for 64 percent of all boilers less than 2.9 MW, while firetubes account for 34 percent. The total 1977 installed heat input capacity of steam and hot water boilers from Tables 3-4 and 3-5 is summarized in Table 3-6. Nearly half of the capacity is provided by natural gas-fired units. Residual oil accounts for nearly one-fourth the capacity and is the second most common fuel used.

The burner assembly of most gas- and oil-fired equipment normally consists of the single power burner designs. However, there are some atmospheric type gas burners installed on the small size equipment such as small cast iron boilers. The majority of the stoker coal units are underfed.

3.2 FURNACE DESIGN PRACTICE

This section reviews the current design practice of units identified in the previous section. Central air and hot water units are discussed in the residential section. For the commercial sector, the various hot water and steam boiler designs as well as some warm air cabinet, rooftop and duct heaters are discussed.

3.2.1 Residential Units

The primary space heating systems in use today include gas- and oil-fired warm air central furnaces, and gas- and oil-fired hot water or steam units, also referred to as hydronic systems. Additionally, the residential sector also includes a great number of smaller floor, room and direct vent heater designs, usually gas-fired. The combustion systems on these units are very similar to the gas-fired warm air furnaces.

3.2.1.1 Gas-Fired Central Air Furnaces

Figures 3-2 and 3-3 show typical gas-fired forced central air furnaces which account for the single largest equipment category*. There are three basic forced air configurations; "high-boy" (up-flow or down-flow), "lo-boy" and horizontal. Typically, for an upflow unit the

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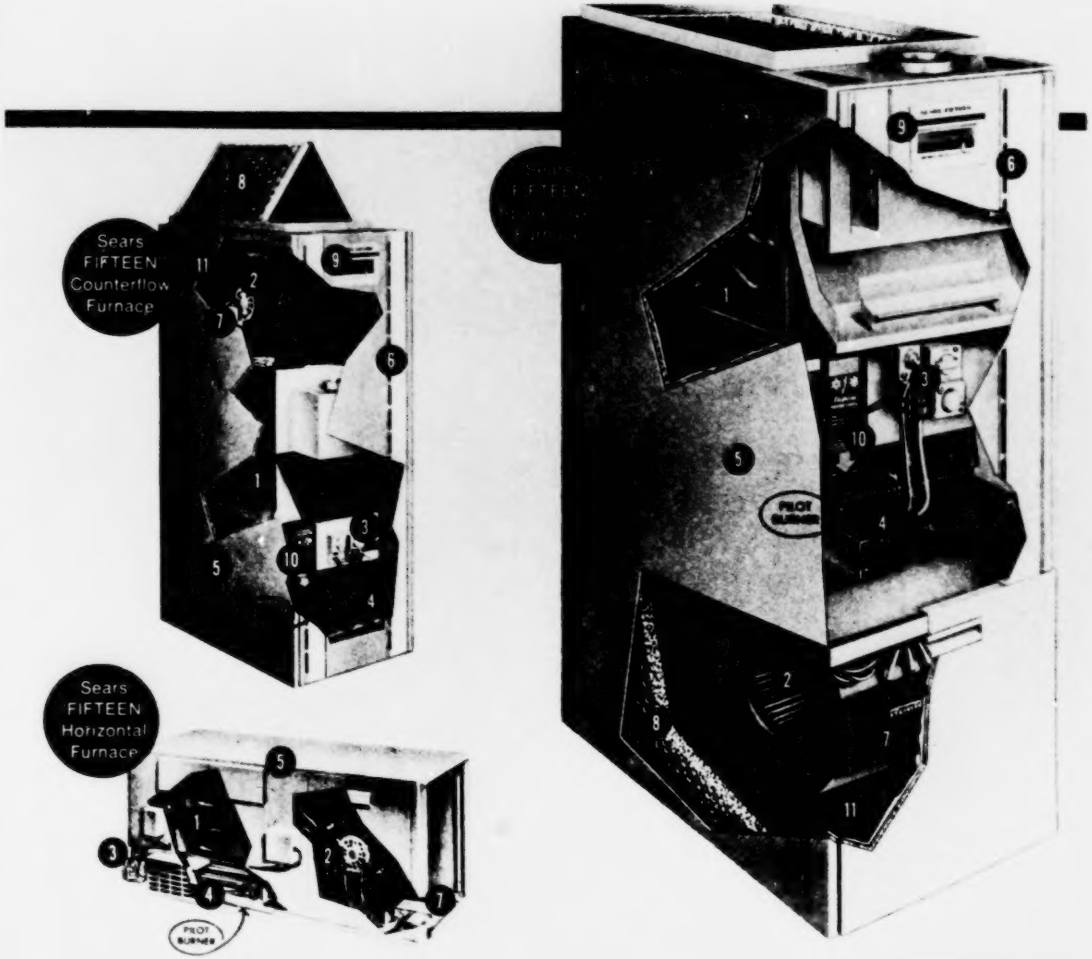
*In the past, there were also a considerable number of gravity or natural draft gas-and oil-fired central air systems. These have fallen out of favor due to the rather large ducts and furnace volume required and the higher cost.

TABLE 3-6. SUMMARY OF INSTALLED CAPACITIES OF COMMERCIAL AND INDUSTRIAL STEAM AND HOT WATER UNITS WITH HEAT INPUT LESS THAN 2.9 MW (10 x 10^6 Btu/hr) -- MW (PERCENT)

Equipment Type	Stoker Coal	Residual Oil[a]	Distillate Oil[a]	Natural Gas[a]	Total
Watertube	1,900 (0.41)	5,240 (1.14)	4,490 (0.99)	5,770 (1.27)	17,400 (3.8)
Firetube	14,420 (3.18)	48,200 (10.62)	31,530 (6.96)	79,090 (17.5)	173,240 (38.2)
Cast Iron	31,590 (6.97)	53,790 (11.9)	33,730 (7.44)	143,520 (31.7)	262,630 (57.9)
Total	47,910 (10.6)	107,230 (23.7)	69,750 (15.4)	228,380 (50.4)	453,270 (100)

[a] Boilers are listed by the primary fuel burned. A large number of units have dual gas/oil fuel burning capability.


Sears FIFTEEN Counterflow Furnace
Sears FIFTEEN Horizontal Furnace
PILOT BURNER
1
2
3
4
5
6
7
8
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10
11

Figure 3-2. Gas-fired forced air furnaces (Reference 3-3).

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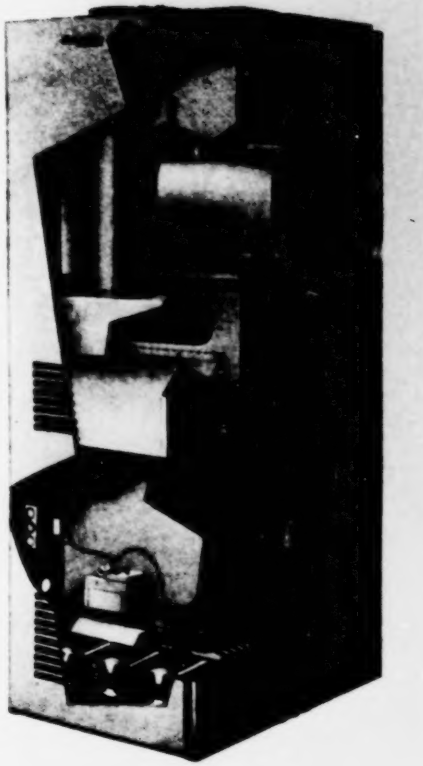
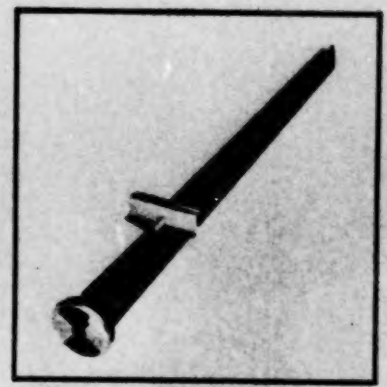
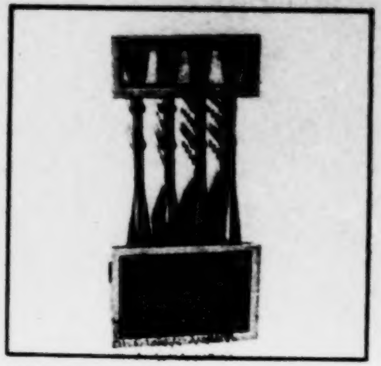
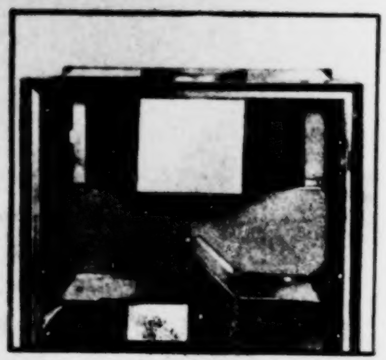




UNIVERSAL SLOTTED PORT STEEL BURNER
Burns Natural And Liquefied Petroleum Gases. Stainless Steel Head.



HEAT EXCHANGER



UNIQUE PATENTED DRAFT DIVERTER

Figure 3-3. Gas-fired forced air downflow furnace and details of components (Reference 3-3).

recirculating room air enters the bottom or side of the unit, flows through the main circulating fan, then to the heat exchanger and usually out the top to the distribution ducting. The gas burners are usually naturally aspirated consisting of venturi three to five primary air shutter and burner ports (single port, ribbon or drilled or formed multiport). The primary air is drawn into the venturi by the expanding natural gas and premixes with the gas prior to ignition. The primary air/fuel ratio can be controlled through the shutter valves at each venturi. After the mixture exits the ports it is ignited by a standing gas pilot or electronic ignitor. Secondary air to complete the combustion reaction enters from the furnace through its secondary air openings and passes around the burners to complete the combustion reaction. The combustion products flow upward through a parallel flow heat exchanger and exit into a collector box or draft diverter. The draft diverters dilute the flue gas stream, prevent downdrafts from blowing out the pilot, and isolate the burner from changes in vent draft. Typical operating conditions are listed in Table 3-7.

Several comments concerning the data of Table 3-7 should be noted. The wide range in excess air levels is due to variations in installation and meterological conditions. The combustion chamber pressures are quite low due to the naturally aspirated design. Consequently, the flue gas flow area is quite large to avoid excessive pressure drop. The low velocity associated with this area results in a fairly low hot side heat transfer coefficient and consequently fairly large surface areas. The furnace relies on the stack to create sufficient draft to draw the secondary air through the furnace. Manufacturers design practice shows that stack temperatures below 422 K (300°F) can yield insufficient draft for the burners and cause condensation in the stack.

3.2.1.2 Oil-Fired Central Air Furnaces

Figure 3-4 shows three common oil-fired forced air furnaces. From the outside these furnaces appear very similar to the gas-fired units and are now being made with overall volumes comparable to gas-fired units. The main difference between the two furnace types is burner design. Most oil-fired burners use pressurized combustion air which mixes with atomized distillate oil as it leaves the nozzle. The gun type oil burner, pictured in Figure 3-5, consists of a combustion air blower, motor, damper, fuel

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TABLE 3-7. TYPICAL OPERATING CONDITIONS FOR A WARM AIR GAS-FIRED FURNACE: 29.3 kW (100,000 Btu/hr)[a]

Recirculating Air Flowrate 0.38-0.57 $W/m^3/s$ (800-1200 SCFM)

Combustion Excess Air: 40-120%

Flue Exit Diameter: 0.089-0.13 m (3.5-5.0 in)

Heat Exchanger Area: 1.9-2.4 m^2 (20-25 ft^2)

Overall Heat Transfer Coefficient: 11-17 W/m^2-K (2-3 Btu/hr-ft^2-°F)

Exit Flue Gas Temperature (Before Draft Diverter): 505-616 K (450-650°F)

Draft Diverter Dilution Air Flow Percent of Flue: 20-50%

Combustion Chamber Pressure: ±50 Pa (± 0.2 in. H_2O)

Temperature Rise on Air Side: 39-55 K (70-100°F)

Overall Steady State Efficiency:[b] 75-80%

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[a] Data is compiled from discusion with manufacturers and from References 3-4, 3-5, 3-6, 3-7, and 3-8.

[b] New furnace must meet American National Standards Institute (ANSI) standards of 75 percent.

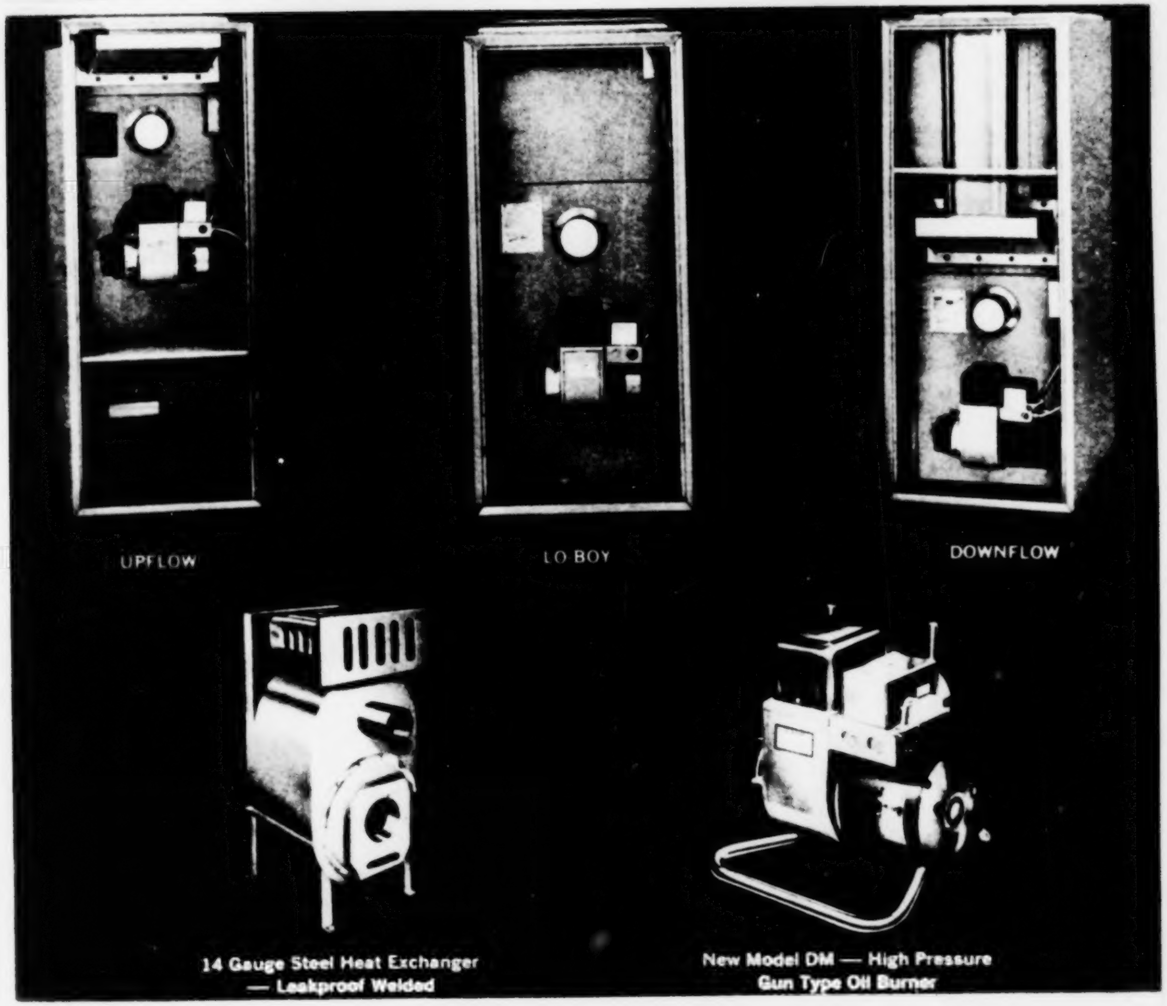
UPFLOW
LO BOY
DOWNFLOW
14 Gauge Steel Heat Exchanger
— Leakproof Welded
New Model DM — High Pressure
Gun Type Oil Burner

Figure 3-4. Oil-fired central air furnaces (Reference 3-3).

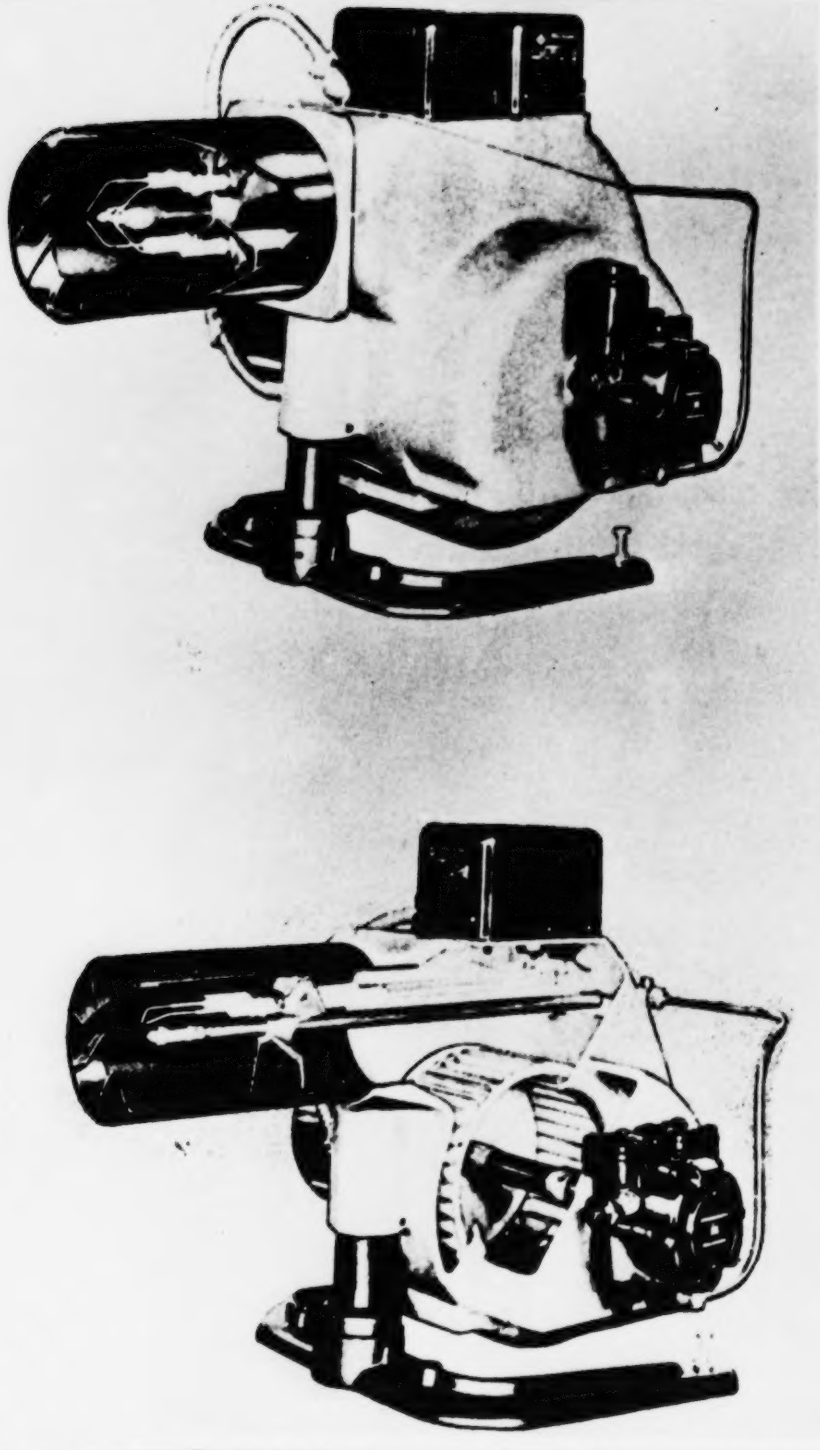

Figure 3-5. Typical high pressure atomizing gun oil burners (Reference 3-3).

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pump, ignition system, main air tube and swirlers, or retention head and fuel nozzle(s). The fuel flowrate is controlled by the size of the orifice in the oil nozzle, while the total air flowrate is controlled by the blower and damper. The proper air/fuel ratio is adjusted using the damper until minimum CO and smoke levels are achieved. Typical operating conditions of oil-fired residential furnaces are summarized in Table 3-8.

The burner is usually mounted in a refractory or refractory felt lined combustion chamber which is cooled by the recirculating room air. From the combustion chamber the flue gases pass through a gas-to-air heat exchanger and finally out the stack. Generally there is no draft diverter in the flue because a forced draft system is used and there is no pilot flame. The burner blower may supply the full pressure to exhaust the flue from the stack or it may rely partially on the buoyancy forces downstream of the furnace.

In recent years the flame retention head burner has become the primary burner design sold. Several types are available with residential burner manufacturers. One design is shown in Figure 3-6. These units usually produce a more stable, compact, and intense flame and will stay in tune (low CO and smoke) longer than previous conventional designs. This flame retention head produces a stable flame by forming recirculation zones in the wake of the flame retention plate. Some swirl is also imparted to the airflow with some burner designs. Oil spray nozzles are pressure atomized often producing a hollow or solid cone spray with a spray angle from 50 to 80 degrees depending on the burner and firebox design. Tuning for low emissions and high efficiency consists of cleaning the burner and nozzle of any deposits (or replacing the nozzle), adjusting the spark ignitors for optimum spark, and adjusting the air damper for minimum CO, smoke and excess air.

The design of the oil-fired burner and heating system is quite empirical and relies on prototype development, experience and testing. Efficiency and standards for construction are set by Underwriters Laboratory and the American National Standards Institute (ANSI).

3.2.1.3 Gas-Fired Hot Water Units

Figure 3-7 shows a typical gas-fired hot water or hydronic heater. New units are usually more expensive than forced air systems and therefore are now being made in the larger capacities of 0.38 MW (130,000 Btu/hr)

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TABLE 3-8. TYPICAL OPERATING CONDITIONS FOR OIL-FIRED CENTRAL AIR SYSTEMS: 29.3 kW (100,000 Btu/hr)

Typical Operating Conditions

Recirculating Air Flow: 0.38-0.57 Nm^3/s (800-1200 SCFM)

Combustion Excess Air: 50-85%

Flue Exit Diameter: 0.13-0.18 m (5.0-7.0 in)

Heat Exchanger Area: 1.9-2.8 m^2 (20-30 ft^2)

Overall Heat Transfer Coefficient: 11-17 W/m^2-K (2-3 Btu/hr-ft^2-°F)

Exit Flue Gas Temperature: 533-589 K (500-600°F)

Combustion Chamber Pressure: 12.5-50 Pa (0.05-0.2 in H_2O)

Temperature Rise on Air Side: 42-44 K (75-80°F)

Overall Steady Efficiency: 75-80%

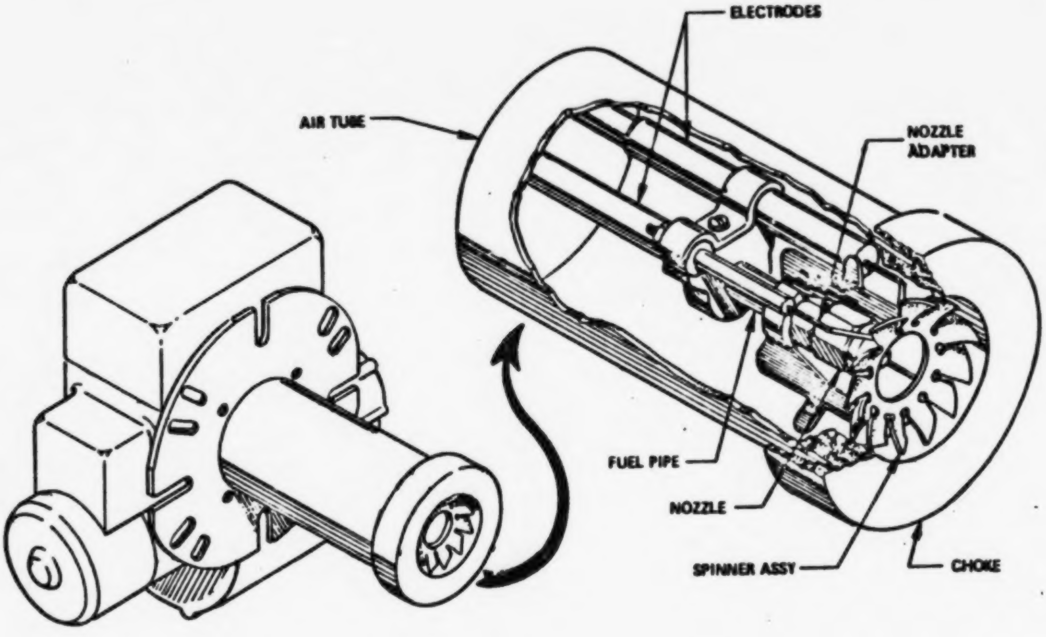
ELECTRODES
AIR TUBE
NOZZLE ADAPTER
FUEL PIPE
NOZZLE
SPINNER ASSY
CHOKE

Figure 3-6. ABC Mite burner with flame retention head (Reference 3-9).

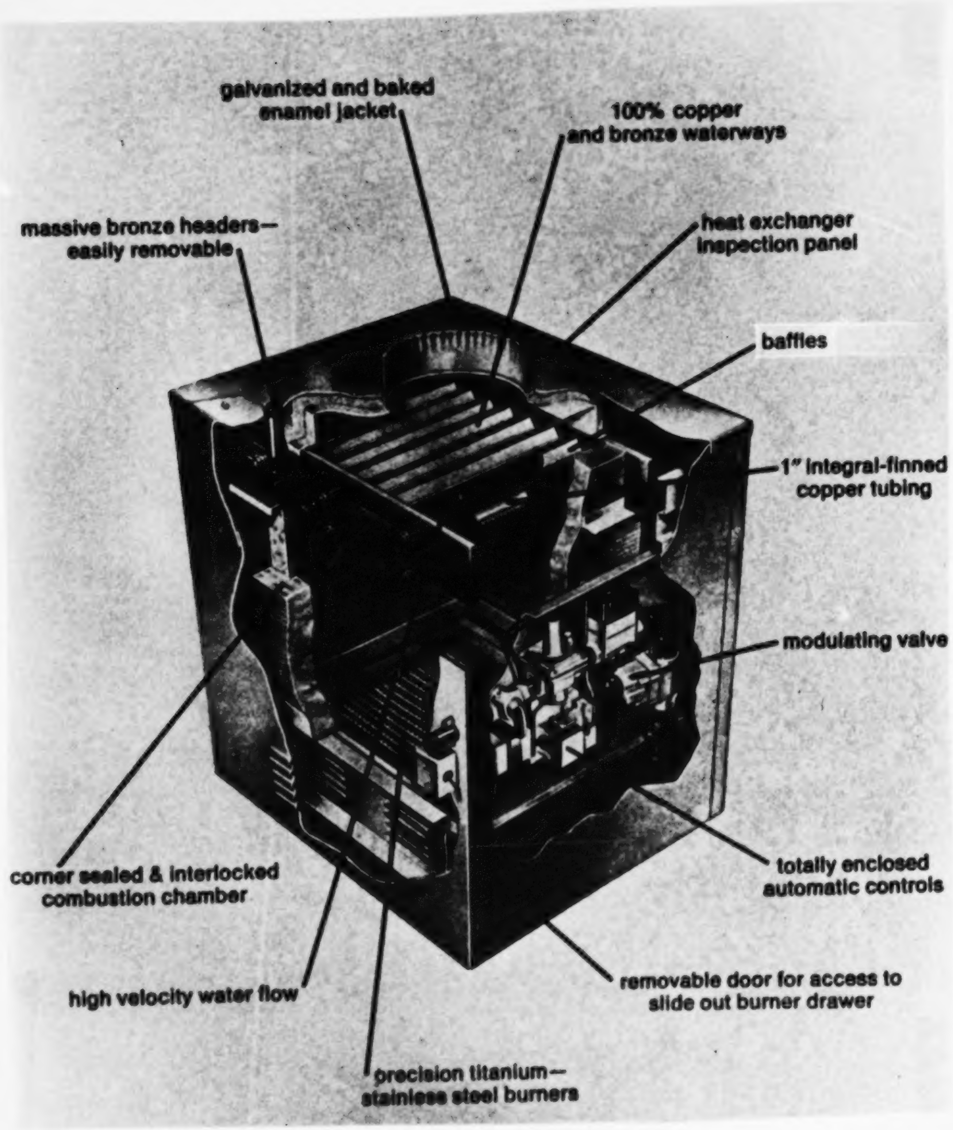
galvanized and baked enamel jacket
100% copper and bronze waterways
massive bronze headers— easily removable
heat exchanger inspection panel
baffles
1" integral-finned copper tubing
modulating valve
totally enclosed automatic controls
corner sealed & interlocked combustion chamber
removable door for access to slide out burner drawer
high velocity water flow
precision titanium— stainless steel burners

Figure 3-7. Gas-fired hydronic boiler (Reference 3-3).

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and above. However, old residential units are still quite prevalent in the Northeastern and Northcentral regions of the U.S. The gas systems on the new units are quite similar to the central air furnace utilizing the naturally aspirated burners. Heat transfer area is governed by the gas side transfer coefficient which is once again limited by the pressure drop requirements of the naturally aspirated burners. Typical operating and design conditions for both oil and gas systems are given in Table 3-9.

3.2.1.4 Oil-Fired Hot Water Units

Figure 3-8 shows the oil-fired hot water system. Again, although quite prevalent in older homes in the Northeast and Northcentral States, they are generally more costly than warm air systems and are often manufactured in larger size ranges for new sales. These units are similar in some respects to the oil-fired warm air central furnaces in that they often employ a refractory lined combustion chamber followed by the heat exchange surface.

3.2.1.5 Stoker Coal-Fired Hot Water and Warm Air Units

Most of the few existing stoker coal-fired residential systems are underfed stoker units. A typical stoker is pictured in Figure 3-9. The coal feed tube delivers the coal to the combustion chamber and also supplies the combustion air. At the end of the feed screw, the coal enters a cast iron chamber or retort where the coal is devolatized. The retort is surrounded by a wind box that supplies combustion air to the fuel bed through slotted holes called tuyeres. In some units, the tuyeres rotate to help break up clinkers and push ash to the outside. Air is supplied by the combustion air blower located under the coal hopper. The airflow is controlled by a damper on the inlet or outlet of the combustion air fan. Ash and clinkers are periodically removed from the outer edge of the fuel bed with a shovel. This material raises to the surface as the coal is fed from underneath the bed. The best coal type for a given design depends on the design of the firebox, retort and air tuyeres. Frequently, a given furnace is adopted to only a limited range of coal types.

The combustion gases pass upward either to water circulating through a boiler or to a heat exchanger to heat recirculated room air. These heat exchanger designs are similar to those used with oil or gas

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TABLE 3-9. TYPICAL OPERATING CONDITIONS FOR OIL- AND GAS-FIRED HOT WATER BOILER WITH 29.3 kW (100,000 Btu/hr) HEAT INPUT

	Gas	Oil
Recirculating Water Flows, m^3/hr (gpm):	0.68-3.4 (3-15)	0.68-3.4 (3-15)
Excess Air, percent:	20-100	30-100
Flue Exit Diameter, m (inches):	0.09-0.13 (3.5-5)	0.09-0.13 (3.5-5)
Exit Flue Gas Temp, K (°F) Upsteam Draft Diverter:	505-588 (450-600)	477-588 (400-600)
Exit Flue Gas Temp, K (°F) (Downstream Draft Diverter):	422-477 (300-400)	422-477 (300-400)
Combustion Chamber Pressure, Pa (in H_2O):	12.5-50 (0.05-0.2)	50 (0.2)
Temperature Rise on Water Side, K (°F)	5.6-22 (10-40)	5.6-22 (10-40)
Overall Steady State Efficiency, percent:	75-80	75-80

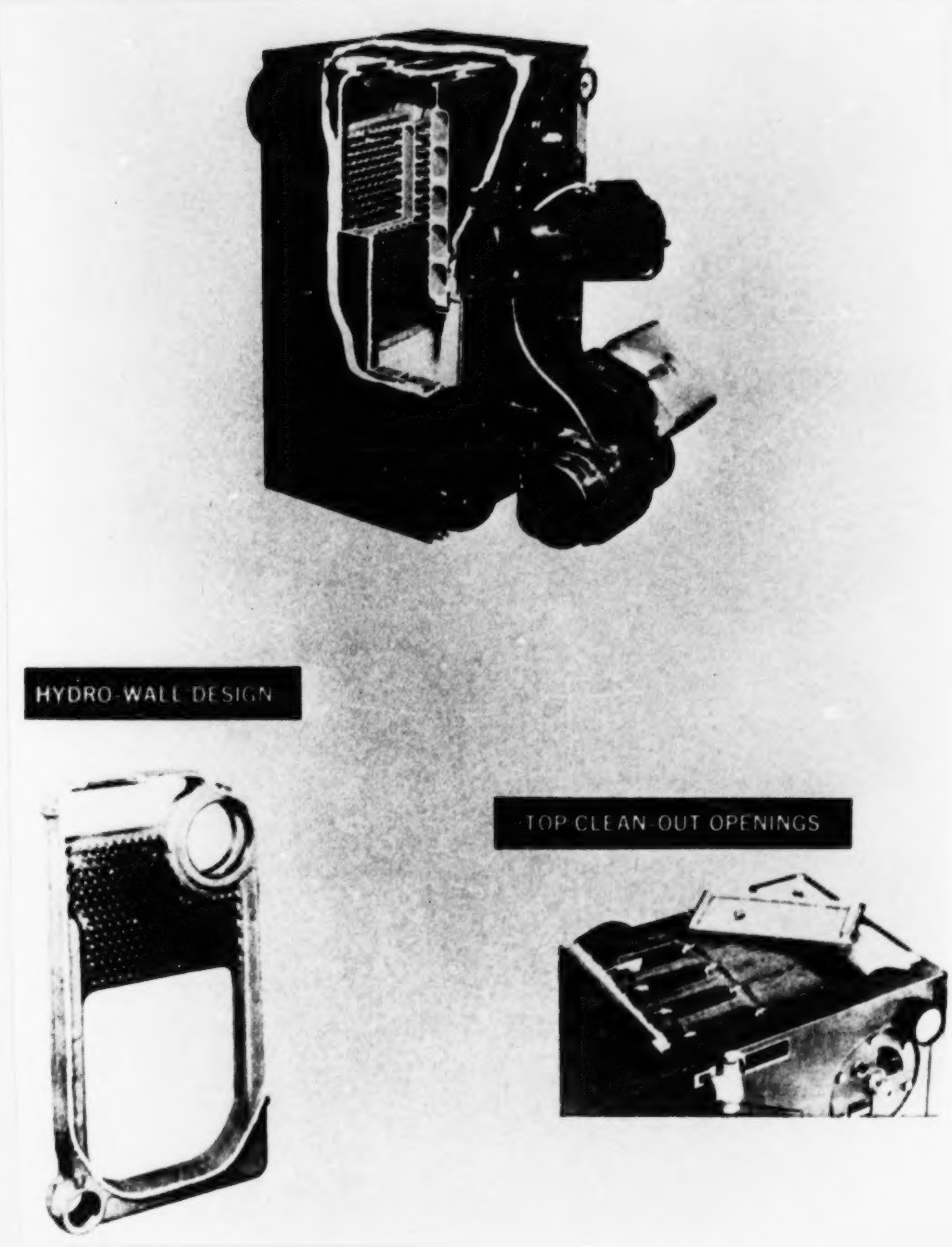
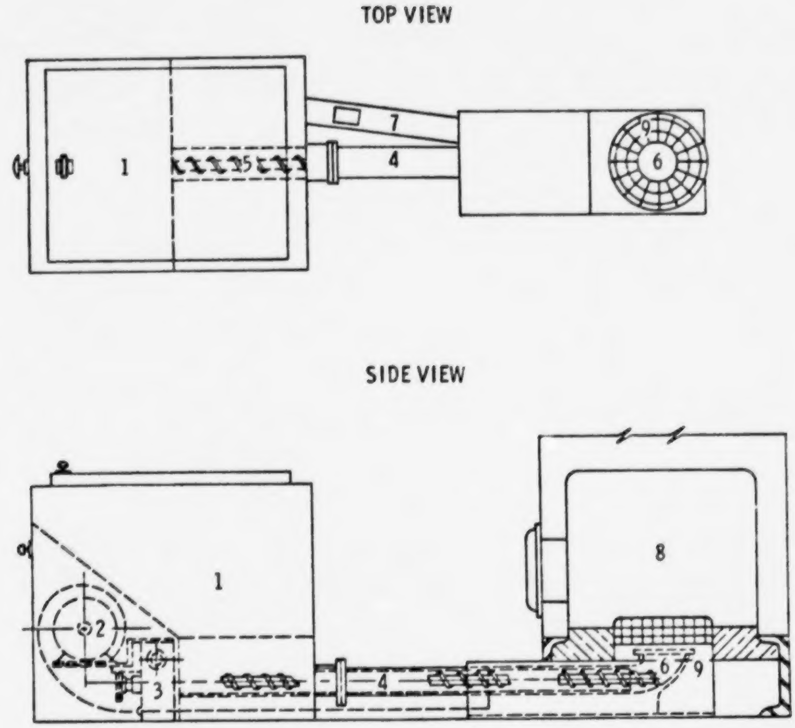

HYDRO-WALL DESIGN
TOP CLEAN-OUT OPENINGS

Figure 3-8. Oil-fired hydronic system (Reference 3-3).


TOP VIEW
1
5
7
4
9
6
SIDE VIEW
1
2
3
4
8
6
7
9

1. HOPPER
2. ELECTRIC MOTOR
3. TRANSMISSION
4. COAL FEED TUBE
5. FEED WORM
6. RETORT
7. RETORT AIR CHAMBER
8. COMBUSTION CHAMBER
9. WIND BOX AND TUYERES

Figure 3-9. Residential heater stoker assembly (Reference 3-10).

except the combustion gas velocities are lower via larger exchange surface spacing to prevent accumulation of ash.

Both the warm air or hot water systems use a barometric damper to control draft through the fuel bed. When the stack is at negative pressure the barometric damper allows room air to enter the exhaust stack. From an emission perspective this is beneficial because the naturally induced air entering the stack dilutes the stack CO and unburned hydrocarbons which occur during transient operation.

3.2.2 Commercial Systems

The major commercial sources include gas-fired warm air systems and gas-, oil-, and coal-fired hot water or steam systems. As noted earlier some hot water and steam systems are also used for industrial process steam. The sections that follow review the current design practice for the types of units that are most popular in the commercial sector.

3.2.2.1 Warm Air Heaters

The four major types of warm air heating systems in the commercial sector are:

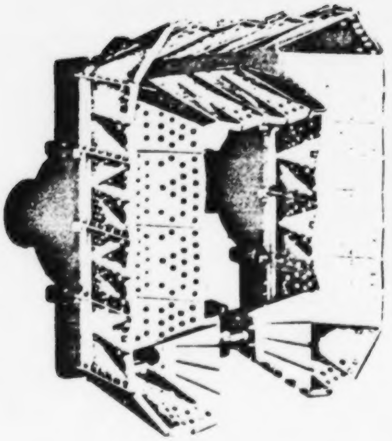
- Packaged units
- Rooftop units packaged as part of central air conditioning
- Duct heaters which are also generally part of a central air conditioning system
- Unit heaters

The packaged type units are scaled-up versions of the residential system. They include the burner and controls, gas to air heat exchanger, air circulation fan, draft diverter and cabinet. There is no appreciable difference in the burner design and operation other than there may be more flue gas distribution tubes for better heat transfer.

Rooftop heaters use either the atmospheric gas-fired combustion system or a power gas- or oil-fired burner. The atmospheric gas burners are identical to the burners used in residential systems incorporating the primary air venturi, gas distribution tubes and a gas to air heat exchanger. Power or pressurized burners in the rooftop units are either gas- or oil-fired. The gas burner is forced draft with a combustion air blower, spark ignitor, fuel delivery system, and some sort of flame retention device. The gas burner will usually fire into a large cylindrical steel combustion chamber and the combustion gases pass through a tubular heat exchanger. In this case a draft diverter is not used. In other power burner designs the fuel and air is premixed and distributed to a number of exit ports in ceramic blocks. These ceramic blocks act as flame holders radiating heat to the heat exchanger surface. Little information is available on the emission characteristics or the population distribution of these commercial systems, especially in relation to the variety of burner designs just described.

The third class of commercial space heating system is the duct heater. These are of two classes -- direct fired and indirect fired. The indirect fired units are placed in line in an air conditioning duct. The majority of duct furnaces are naturally aspirated gas-fired units similar in design to warm air furnaces. The direct fired duct heater or make-up air heater as shown in Figure 3-10 usually includes the air fan that supplies a portion of the total air for a commercial building. These are exclusively natural gas-fired units and the products of combustion are combined with the air circulated to the space being heated. The burners are unique in that they are placed in the delivery air duct and the total room air supply passes through the burners. The hole pattern in the burner assembly allows for a slow mixing of this diluent air thus preventing rapid quenching of the flame and high CO levels.

The unit heater is a variation of the indirect fired duct heater. Unit heaters are self contained systems with a fan, burner and heat exchanger. They usually are mounted from the ceiling to supply warm air only to the room in which they are located. These heaters, although usually gas-fired, may also be propane or oil-fired. One type of unit heater design, usually natural gas-fired, operates by heating ceramic elements which in turn radiate in the infrared wavelength range to the object or area being heated. This type of heater is frequently used where a very localized area requires heating. In the gas-fired unit the combustion takes place at the surface of the ceramic tile. All the combustion air is aspirated by the gas expansion similar to warm air furnace burners. No combustion air blower or air circulating fan is required. The combustion products exit directly into the room but pollutant levels are quite low because of nearly complete combustion at the ceramic tile.



Airflow Line
Burner

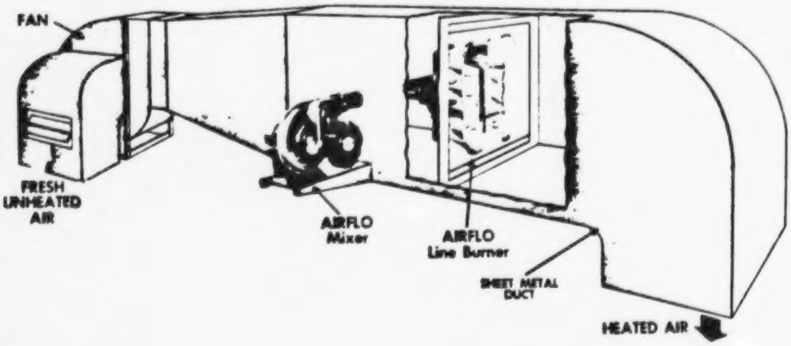

FAN
FRESH UNHEATED AIR
AIRFLO Mixer
AIRFLO Line Burner
SHEET METAL DUCT
HEATED AIR

Figure 3-10. Direct gas-fired duct heater and line burner assembly (Reference 3-11).

3.2.2.2 Hot Water or Steam Systems

In the size range of 0.1 to 2.9 MW (0.4 to 10 x 10^6 Btu/hr) there are over 10 different boiler designs adapted to be either gas- or, oil-, or coal-fired. These designs can be grouped in three major categories: watertube, firetubes, and cast iron boilers. Figures 3-11 and 3-12 show schematics of watertube and firetube designs, respectively. Cast iron hydronic designs are described in Section 3.3.1.3 for residential hot water units; commercial or industrial cast iron units are of similar design. Both commercial watertube and firetube designs are similar to the small industrial size boiler designs which are assessed in another NO_x EA report (Reference 3-12). However, a brief description of firetube and cast iron boilers, which represent over 95 percent of the installed commercial hot water or steam capacity, is given. There are four major firetube boiler designs -- scotch, horizontal return tube (HRT), firebox, and vertical.

Scotch Firetube

This boiler design, developed over 30 years ago is the most popular of the firetube boilers. Scotch firetube boilers are available in two-, three-, or four pass units with the boiler and furnace contained in the same shell. The heat input capacity for these units is normally less than 2.9 MW (10 x 10^6 Btu/hr). They account for almost 40 percent of total firetube capacity in this size range, and can burn a variety of fossil fuels. However, coal-fired units are not common because of slagging and scaling problems.

Horizontal Return Tubular (HRT)

The HRT boiler and furnace is generally lined with brick. The boiler, which is set horizontally, rests above the refractory brick furnace. The HRT design accounts for about 11 percent of the installed capacity in the size category less than 2.9 MW (10 x 10^6 Btu/hr). The boiler comes with two-, three-, or four-passes and can burn all types of fossil fuels. Coal is burned on a grate.

Firebox

The firebox design employs two- or three-passes depending on whether the boiler is the short or compact type. Similar to the Scotch design, the furnace is steel encased, water jacketed, and internal to the

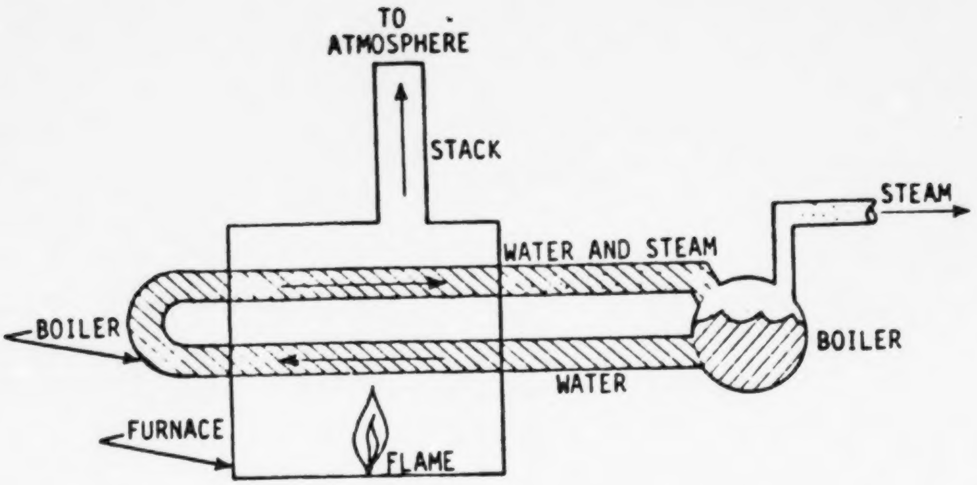

TO ATMOSPHERE
STACK
STEAM
WATER AND STEAM
BOILER
BOILER
WATER
FURNACE
FLAME

Figure 3-11. Simplified diagram of a watertube boiler (Reference 3-2).

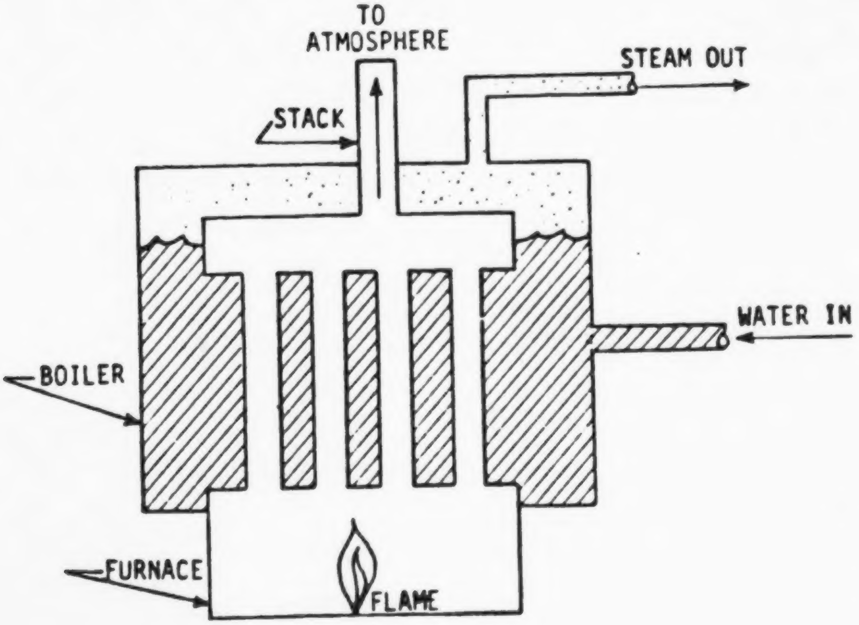

TO ATMOSPHERE
STEAM OUT
STACK
WATER IN
BOILER
FURNACE
FLAME

Figure 3-12. Simplified diagram of a firetube boiler (Reference 3-2).

boiler. Firebox units are designed with heat input capacities as high as 5.8 MW (20 x 10^6 Btu/hr) and have an advantage of compactness and high efficiency. Below 2.9 MW (10 x 10^6 Btu/hr) they account for almost 45 percent of the total installed firetube capacity.

Vertical

With the vertical design, the firetubes are vertical instead of horizontal as with the other designs. The tubes can be either submerged in water or partially exposed to steam. Figure 3-13 shows the partially exposed tube design. Submerged tube designs have been abandoned because of their tendency to leak. Capacities of these units are generally lower than 0.75 MW (2.5 x 10^6 Btu/hr) and have a maximum efficiency of about 70 percent (Reference 3-2). These units comprise less than 5 percent of total firetube capacity.

Coal-fired systems in the size category below 2.9 MW (10 x 10^6 Btu/hr) are all stoker or hand fed. Three designs of watertube and firetube coal-fired stokers, are in use -- underfed, overfed, and spreader stokers. Underfed stokers, account for about 80 percent of coal-fired boilers with heat input below 2.9 MW (10 x 10^6 Btu/hr). These units feed raw coal from below the fuel bed. Overfeed stokers account for approximately 10 percent of coal-fired boiler capacity. They are less popular because of higher cost, which is about twice that of an underfeed stoker unit. Spreader stokers account for less than 10 percent of the capacity in the commercial size range. The coal in the spreader stoker burns partially in suspension. Combustion is completed on a moving or stationary vibrating grate. Further details on the stoker designs are given in the NO_x EA report on industrial boilers (Reference 3-12).

3.2.2.3 Cast Iron

The commercial cast iron boiler consists of an assembly of cast iron sections with water or steam on one side and combustion gases on the other. Frequently the cast iron surface is either ribbed or studded to provide extended heat transfer surface area. The size of the boiler is determined by the number of sections sandwiched together. Although these units are more expensive than firetube boilers, they are also more reliable, durable, and require less maintenance. As with residential units they are usually naturally aspirated when fired with gas, or fitted with a gun type oil burner.

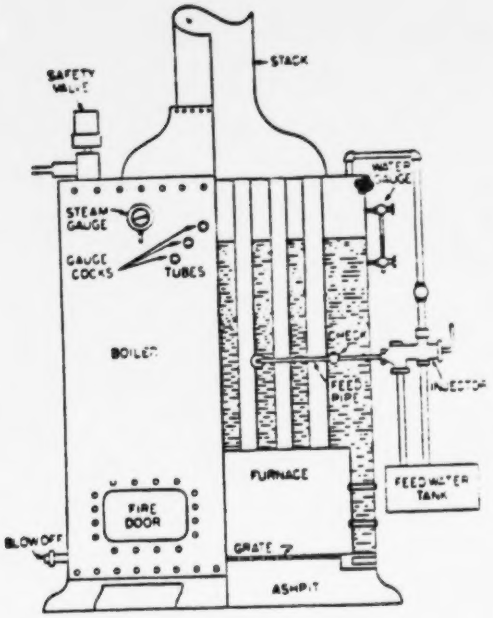

SAFETY VALVE
STACK
WATER GAUGE
STEAM GAUGE
GAUGE COCKS
TUBES
BOILER
CHECK
FEED PIPE
INJECTOR
FURNACE
FEEDWATER TANK
FIRE DOOR
BLOWOFF
GRATE
ASHPIT

Figure 3-13. Exposed-tube vertical boiler (Reference 3-2).

With a gas-fired unit the entire bottom of the boiler is open to allow combustion air to be drawn into the unit by the draft of the flue gases. With oil firing, a firebox cavity is built into the unit and the system is intended to be sealed. Design and construction of these units are governed by ASME Boiler Code for pressurized vessels and are tested and rated by the Hydronics Institute. The Hydronics Institute provides an Industrial Boiler Rating (IBR) in accordance with minimum efficiency, percent CO_2, flue gas temperature, and smoke emissions.

3.3 AREAS OF ENVIRONMENTAL CONCERN

This section identifies areas of environmental concern for the residential, commercial and industrial combustion equipment types with heat input capacities of 0.1 to 2.9 MW ($0.4\text{-}10 \times 10^6$ Btu/hr). Major pollution streams identified here are then quantified in Section 4. Table 3-10 summarizes pollution streams from these combustion units. As indicated, combustion products exiting the stack constitute the major environmental concern for all equipment types. For coal-fired equipment, ash disposal is also an area of environmental concern due to quantities of ash generated and some potentially toxic constituents in the ash. Leakage

TABLE 3-10. EMISSION STREAMS FROM RESIDENTIAL AND COMMERCIAL UNITS

Emission Streams	Gas- and Oil-Fired Systems				Coal- and Wood-Fired Systems			Remarks
	Residential Warm Air Furnace	Residential Hot Water Heater	Residential & Commercial Direct Fired Heater	Commercial Hot Water and Steam Boilers	Residential Warm Air Furnace	Residential Hot Water Heater	Commercial Hot Water and Steam Boiler	
Combustion products from the stack	M	M	M	M	M	M	M	Major pollutants in the flue gas include NO_x, HC, and CO. In addition, particulate (smoke) and SO_x when burning oil or coal.
Combustion products leakage into heated air	m		m		m			Combustion products leakage across heat exchanger with some older units. Some leakage from ducts into surrounding space also possible.
Solid ash waste disposal					M	M	M	Ash wastes to disposal site. Potentially leachable trace elements in the ash. Major concern with coal.
Combustion products mixed with heated air			M					Direct fired heaters are primarily gas fired. Major pollutants are NO_x, CO, and HC.
Fuel Supply leakage	m	m	m	m	m	m	m	Leakage of gas and oil only an accidental occurrence. Coal dust as fugitive emissions.

M -- major pollutant stream
m -- minor pollutant stream.

of combustion products into habitated areas may occasionally cause environmental concern with some older units. These three streams -- stack emission, combustion products leakage, and solid waste -- are briefly discussed below.

3.3.1 Stack Emissions

Pollutant emission of NO_x, CO, and unburned hydrocarbons (UHC) in varying concentrations are emitted from the stack along with H_2O, CO_2, N_2, and oxygen for all fuels burned. Levels of sulfur and inorganic compounds, negligible with natural gas and distillate oil combustion, are significant when residual oil and coal are burned. Sulfur and ash in the residual oil and coal convert to SO_2 emissions and particulate matter respectively and exit with the flue gas. Air pollutant emissions from coal are often emitted in greater quantity than emissions from gas and oil combustion. Conversion of fuel bound nitrogen in the coal contributes to emissions of NO_x, which are generally higher than those of units fired with gas or oil. Also carbon monoxide as well as nonmethane hydrocarbon emissions from coal are often higher than those from gas and oil combustion.

The largest emission levels of CO, UHC, and smoke occur during lightoff and shutdown periods. Because of the cyclic nature of most heating systems, the furnace often never reaches equilibrium condition. The CO, UHC, and smoke problem associated with cyclic operation is further aggravated when the system is oversized. In such cases, cycle frequency is usually higher with a correspondingly low on-period.

3.3.2 Leakage of Combustion Products

Leakage of the combustion products into the heated space may occur in a number of areas in the furnace system. Of primary importance is the possibility of leakage across the heat exchanger of a warm air furnace. Many gas utilities will shut off the gas supply to a unit that has visible cracks in the heat exchanger. Overall, unless residential heating equipment is relatively old, leaks are not a serious environmental concern.

In a home installation the house air is usually recirculated from the rooms to the furnace and back to the rooms. If there is leakage from the furnace system potentially the air quality in the rooms would deteriorate. However, usually there is sufficient make-up air in buildings through leaks in windows, doors, etc., to prevent this problem.

As greater emphasis is given to energy conservation and the sealing of leaks into the house (air infiltration accounts for the largest load in residential heating) attention should be paid to the air quality within the home. Sufficient air must always be brought into the home for the combustion process. In commercial systems frequently make-up air is brought into a building so that a certain number of ambient air changes per hour is maintained. Some commercial heating systems also rely on an outside air supply for combustion.

3.3.3 Solid Waste Streams

The solid waste stream (although intermittent) in the form of bottom ash clinkers is of environmental concern for coal-fired residential and commercial size units. These clinkers usually find their way to a refuse disposal site in urban areas where trace contaminants in the ash can be leached out by rainfall. In rural areas they are usually buried or disposed in a local waste disposal site where leaking can also occur.

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SECTION 4

CHARACTERIZATION OF FUELS, PRODUCTS AND AIR EMISSIONS

This section summarizes the physical and chemical characteristics of fuels burned and waste streams (primarily flue gas) for residential and commercial heating systems described in Section 3. A recent air pollutant emission inventory is also presented for selected systems.

4.1 SUMMARY OF SAMPLING AND ANALYTICAL ACTIVITIES

Activities to quantify air pollution emissions and determine control potential in residential/commercial heating have centered primarily on residential heating furnaces and commercial steam and hot water units. Less is known of the emissions of various commercial warm air heating systems.

Table 4-1 summarizes major laboratory and field studies performed on residential and commercial heating equipment. The table lists the specific type of equipment tested, the organization performing and sponsoring the work, the completion date of the study and the principal pollutants sampled. Information on the emission controls investigated is also listed. Major results of these studies will be reviewed in the following sections of this report.

As the table indicates, the bulk of the sampling and analytical activity for the gas-fired residential and commercial space heaters and boilers has been sponsored by the EPA and by the American Gas Association Laboratories (AGAL). Some work specific to oil-fired systems has been jointly sponsored by the American Petroleum Institute (API) and the EPA. Tests primarily related to energy consumption and conservation (with limited emission data taken) were not included in this table. These tests have been performed for the National Science Foundation (NSF), Federal Energy Administration (FEA), and the Department of Energy (DOE).

TABLE 4-1. SUMMARY OF MAJOR SAMPLING AND ANALYTICAL ACTIVITIES ON RESIDENTIAL AND COMMERCIAL HEATING SYSTEMS

General Equipment Category	Specific* Equipment Tested	Organization Performing Work	Sponsoring Organization	Completion Date	Emissions Evaluated								Pollution Controls	Ref.
					NO_x	CO	HC	SO_x	Part.	Smoke	Trace Elements	Organics		
Gas-Fired Indirect Heating	SFB, FFB, FAF	Battelle Columbus Labs.	American Petroleum Institute (API)	1971	X	X	X	X	X	X			Tuning	4-1
	FAF	American Gas Association (AGA)	American Gas Association (AGA)	1975	X	X	X						Radiant screens secondary air baffles	4-2
	HWB	The Research Company (TRC)	American Gas Association (AGA)	1974	X	X	X		X				None	4-3
	FAF	American Gas Association (AGA)	Gas Appliance Manufacturers Association (GAMA)	1978	X	X							None	4-4
	FAF, HWB, VH USH, WH	American Gas Association (AGA)	American Gas Association (AGA)	1974	X	X	X						Radiant screens secondary air baffles and burner mods	4-5
	FAF, CIB, SFB, FFB, WB	Battelle Columbus Labs.	American Petroleum Institute (API) and EPA	1973	X	X	X	X	X	X			Tuning, replace., burner	4-6

*Specific equipment tested

SFB = Scotch Firetube Boiler
FFB = Firebox Firetube Boiler
HWB = Hot Water Boiler
VH = Vented Heater
WS = Wood Stove
USH = Unvented Space Heater
WH = Wall Heater
WB = Watertube Boiler
BSFB = Bituminous Stoker Firetube Boiler
FP = Fireplace
FAF = Forced Air Furnace
CIB = Cast iron boiler

TABLE 4-1. Continued

General Equipment Category	Specific* Equipment Tested	Organization Performing Work	Sponsoring Organization	Completion Date	Emissions Evaluated								Pollution Controls	Ref.
					NO_x	CO	HC	SO_x	Part.	Smoke	Trace Elements	Organics		
Gas-Fired Indirect Heating (continued)	FAF, HWB	EPA	EPA	1974	X	X	X			X			Burner and combustion mods	4-7
	FAF	Lawrence Berkeley Labs., U.C.	ERDA (DOE)	1976	X	X		X					None	4-8
	UVH	The Research Corp. (TRC)	EPA	1974	X	X							None	4-9
	FAF, WB, SFB, FFB	TRW	EPA	1979 - Ongoing	X	X	X	X	X	X	X	X	None	4-10 4-11
Gas-Fired Direct Heating	Maxon Makeup Air Burners	IGT	Maxon	1969	X	X	X						None	4-12
Oil-Fired Indirect Heating	SFB, FFB, FAF CIB, HWB, WH	Battelle Columbus Labs.	American Petroleum Institute (API)	1971	X	X	X	X	X	X			None	4-1
	FAF, HWB, WH, SFB, FFB, CIB, WB	Battelle Columbus Labs.	API and EPA	1973	X	X	X	X	X	X			Tuning, Replacement and burner mods.	4-6

*Specific equipment tested

SFB = Scotch Firetube Boiler
FFB = Firebox Firetube Boiler
HWB = Hot Water Boiler
VH = Vented Heater

WS = Wood Stove
USH = Unvented Space Heater
WH = Wall Heater
WB = Watertube Boiler

BSFB = Bituminous Stoker Firetube Boiler
FP = Fireplace
FAF = Forced Air Furnace
CIB = Cast iron boiler

TABLE 4-1. Continued

General Equipment Category	Specific* Equipment Tested	Organization Performing Work	Sponsoring Organization	Completion Date	Emissions Evaluated: NO_x	CO	HC	SO_x	Part.	Smoke	Trace Elements	Organics	Pollution Controls	Ref.
Oil-Fired Indirect Heating (continued)	FAF, HWB	EPA	EPA	1974	X	X	X			X			Burner & combustion mods.	4-7
	FAF	U.S. Dept. of H.E.W.	NAPCA/EPA	1970	X	X	X						Flame retention burner	4-13
	HWB	Langley Research Center	NASA	1976							X		None	4-14
	WH, FAF	Canadian Combustion Research Lab. (CCRL)	Canada Centre for Mineral and Energy Technology	1978	X	X				X			Water-oil emulsion	4-15
	FAF	Rocketdyne Div. Rockwell International	EPA	1976 to 1979	X	X	X			X			Burner & furnace development	4-16 4-17 4-18 4-19
	FAF	Acurex	EPA	1979	X	X	X	X	X	X	X	X	Low emission high efficiency furnace	4-20
	FAF SFB	EPA	EPA	1975 to 1979	X	X			X	X		X	Water-oil emulsion	4-21 4-22 4-23

*Specific equipment tested

SFB = Scotch Firetube Boiler
FFB = Firebox Firetube Boiler
HWB = Hot Water Boiler
VH = Vented Heater

WS = Wood Stove
USH = Unvented Space Heater
WH = Wall Heater
WB = Watertube Boiler

BSFB = Bituminous Stoker Firetube Boile
FP = Fireplace
FAF = Forced Air Furnace
CIB = Cast iron boiler

TABLE 4-1. Concluded

General Equipment Category	Specific* Equipment Tested	Organization Performing Work	Sponsoring Organization	Completion Date	Emissions Evaluated								Pollution Controls	Ref.
					NO_x	CO	HC	SO_x	Part.	Smoke	Trace Elements	Organics		
Oil-Fired Indirect Heating (continued)	FAF	EPA	EPA	1980	X	X	X	X	X	X	X	X	None	4-24
	FAF, WB SFB, FFB	TRW	EPA	1979 to ongoing	X	X	X	X	X	X	X	X	None	4-10 4-11
Coal-Fired Indirect Heating	BSFB	Battelle Columbus Labs	EPA	1976	X	X		X	X	X		X	Coal Switching	4-25
	FAF, HWB	Monsanto Research Corporation	EPA	1978	X	X	X	X	X		X	X	None	4-26
	FAF, HWB	Battelle Columbus Labs	Bituminous Coal Research (BCR)	1978						X			Furnace Development	4-27
Wood-Fired Indirect Heating	WS, FP	Monsanto Research Corporation	EPA	1980	X	X	X	X	X		X	X	Tuning	4-28
	WS	Battelle Columbus Labs	EPA	Ongoing	X	X	X	X	X		X	X	Process Modifications	4-29

*Specific equipment tested

SFB = Scotch Firetube Boiler
FFB = Firebox Firetube Boiler
HWB = Hot Water Boiler
VH = Vented Heater
WS = Wood Stove
USH = Unvented Space Heater
WH = Wall Heater
WB = Watertube Boiler
BSFB = Bituminous Stoker Firetube Boiler
FP = Fireplace
FAF = Forced Air Furnace
CIB = Cast iron boiler

A large number of the test programs listed in Table 4-1 were performed under laboratory conditions allowing for the monitoring of many test parameters. Carbon monoxide (CO), unburned hydrocarbons (UHC), NO_x, SO_2, smoke, and filterable particulate matter were the principal pollutants of interest tested. Trace metals and organic emissions were determined primarily with coal and wood combustion.

4.2 FUELS

Over 90 percent of residential furnaces and small commercial heaters burn natural gas or distillate oil. Residual oils which require heating for efficient atomization and combustion are generally burned in the larger commercial equipment. Coal is still used in some residential furnaces and hot water heaters. The increasing scarcity of the cleaner gas and distillate oil fuels has renewed interest in coal and wood firing for residential and commercial applications. However, economic and environmental considerations still dictate the use of natural gas or distillate oil as the primary fuels for the small residential systems.

4.2.1 Gaseous Fuels

Natural gas is the most common fuel for residential and commercial space heating and commercial hot water or steam production. Approximately 55 percent of the residential and commercial equipment with heat input less than 2.9 MW (10×10^6 Btu/hr) is fired with this fuel. Natural gas, which is relatively clean burning and easy to handle, is the primary fuel used for direct fired commercial heaters in which the combustion products are mixed directly with heated air. However, some oil-fired portable direct space heaters are being used commercially mainly for construction jobs, garages, barns, etc.

Primary air pollutants emitted from gas-fired units include NO_x, CO, and hydrocarbons. Particulate matter and sulfur oxides are generally minimal and do not pose an environmental concern. Other gaseous fuels used in the residential sector include bottle butane or propane, also known as liquid petroleum gas (LPG). Nearly half of domestic LPG consumption is for warm air furnaces and steam and hot water hydronic boilers.

The continuously rising cost of natural gas may in the future lead to significant use of electric heat or alternate gaseous fuels for residential and commercial space heating. One such alternate fuel is the high Btu gas produced from the gasification of coal. High Btu gas, also referred to as synthetic natural gas (SNG), is a pipeline quality gas essentially identical in composition to natural gas. Thus, SNG can use the same distribution and combustion system now being used for natural gas. However, at present, there is no commercial high Btu gas plant supplying pipeline networks carrying natural gas. The Lurgi methanation process has been demonstrated to be the most technically feasible of all high Btu gasification processes. However, high capital and operating costs may preclude the commercial availability of this alternate gaseous fuel until the late 1980's. In the meanwhile, as natural gas supplies become increasingly scarce, it is possible that more industrial users will be made to switch to alternate fuels to leave sufficient natural gas for existing residential and commercial heating installations.

4.2.2 Liquid Fuels

Liquid fuels for residential heating are almost entirely distillate oils, while commercial and industrial units in the size range of 0.1 to 2.9 MW (4×10^5 to 10×10^6 Btu/hr) burn both distillate and residual oils.

There are various grades of fuel oil available today in the United States. These oils are classified according to their physical characteristics as shown in Table 4-2. Grades No. 1 and No. 2 are distillate oils while Grades No. 5 through No. 6 are residual oils. The table also describes low sulfur residual oil which is a fuel growing in popularity, especially in those areas with stringent sulfur emission regulations. Grade No. 4 oil can be either a distillate or a mixture of distillate and residual oil (Reference 4-34). The No. 2 fuel oil accounts for about 75 percent of the distillate fuel consumption in residential heating systems. The remainder of the domestic oil demand is met with No. 1 grade oil (Reference 4-35). Residual oil accounts for about 60 percent of all oil burned in commercial and industrial equipment with heat input less than 2.9 MW (10×10^6 Btu/hr) (Reference 4-36).

Methanol and water-in-oil emulsions have also been investigated as alternate liquid fuels for residential and commercial space heating equipment. Methanol is currently produced from the synthesis of natural gas. However, there is currently strong interest in methanol generation

TABLE 4-2. FUEL OIL DESIGNATION AND TYPICAL CHARACTERISTICS (Reference 4-30)

Grade^{a}	Description and Application	Preheating Requirement		Viscosity Range	Typical API Gravity
		For Pumping and Handling	For Burning	Saybolt Universal at 100°F^{e}	Sec. at 60°F^{f}
No. 1	Light distillate oil intended for vaporizing pot-type burners. Seldom used for pressure-type oil burners or commercial burners.	No	No	--	42
No. 2	Medium distillate oil for general purpose domestic and commercial heating equipment.	No	No	33-38 SSU (35)	35
No. 3	Obsolete grade designation.	--	--	--	--
No. 4	Heavy distillate oil that may contain some residual oil. Suitable for firing most commercial burners.	Usually No^{c}	Usually No^{c,d}	45-125 SSU (80)	19
No. 5 Light	Light residual oil for commercial-industrial burners. Generally contains a larger blended portion of distillate oil than No. 5 Heavy. Usually requires preheat for burning but not for handling.	Usually No^{c}	Usually Yes^{c}	125-300 SSU (200)	18
No. 5 Heavy	Medium-viscosity residual fuel oil for commercial-industrial burners. Usually requires preheat for burning.	Usually No^{c}	Yes	300-900 SSU (550)	16
No. 6	High-viscosity grade of residual fuel oil for the largest commercial-industrial burners with full preheating. Sometimes referred to as "Bunker S".	Yes	Yes	900-9000 SSU (5000)	13
Low-Sulfur Resid^{b}	Residual fuel oil for commercial-industrial burners that is refined or blended to meet local sulfur regulations	Usually No^{c}	Usually Yes^{c}	45-9000 SSU	--

[a] Grade numbers No. 1, No. 2, No. 4, No. 5 (light), No. 5 (heavy), and No. 6 are ASTM designations (Reference 4-31).

[b] "Low-sulfur resid" is a recent term used to describe residual oil grades recently shipped to meet local regulations; it is essentially replacing No. 5 and No. 6 where sulfur regulations are in effect, for example, along the East Coast. (The sulfur content of this grade of fuel oil is generally 1 percent, or less.) The viscosity of present low-sulfur resid is in the range of No. 5 (Reference 4-32). (It is not clear what the viscosity of these fuels may be in the future.)

[c] Preheating requirement depends on pour-point and viscosity in relation to climate.

[d] May require heating for burning when using mechanical atomization.

[e] Viscosity limits specified by ASTM D396-75 for number grade shown. Range for low-sulfur resid is estimated. Average viscosity for U.S. refined fuels from ERDA Heating Oils Survey, 1975 (Reference 4-33) is shown in brackets and is presented as a typical value.

[f] Average API gravity for U.S. refined fuels from ERDA Heating Oils Survey, 1975 (Reference 4-33).

from biomass. Combustion of methanol in an experimental hot wall furnace produced approximately 75 percent less NO_x than distillate oil combustion (Reference 4-37).

Water-in-oil emulsions have been investigated as a means to increase efficiency of residential furnaces as well as to reduce NO_x emissions. NO_x emission levels from emulsions with approximately 50 percent water in distillate oil by mass approached the levels obtained from methanol combustion (Reference 4-38). The EPA program also tested emulsions in one residential and one commercial unit using three commercially available water/oil emulsifiers (References 4-21, 4-22, and 4-23). The laboratory study concluded that NO_x, smoke and particulate mass are reduced while CO and HC were not significantly affected using up to 32 percent water-in-oil emulsions. Efficiency dropped sharply when the percentage of water in the emulsion exceeded 18 percent. NO_x reductions ranged from about 15 to 50 percent depending on the type of emulsifier and source used. With water/residual oil emulsion tests, no significant effects on NO, SO_2, HC or CO emissions were reported (References 4-22 and 4-23). The little change in NO emissions compared to tests with distillate oil was attributed to the ineffectiveness of water emulsion in reducing fuel nitrogen conversion to NO_x. Particulate mass emissions decreased with increasing percent water in the residual oil (up to 30 percent water in oil was tested) (Reference 4-22). However, the total amount of fine particulate emissions was found to increase (Reference 4-23). Boiler efficiency changes varied from +1 to -7 percent with excess air levels set at emission smoke limits for both oil only and water-in-oil tests (Reference 4-23).

Recent studies on two residential heating systems showed that over 10 percent water content in the distillate oil is impractical because it leads to increased CO emissions (Reference 4-15). Furthermore, the increase in combustion efficiency with 10 percent water content was found to be modest (less than 2.6 percent). This slight improvement in efficiency does not warrant operating difficulties such as ignition difficulties, pump failures, combustion instabilities and corrosion of water-in-oil emulsions (Reference 4-15). These results agree with EPA test results.

4.2.2.1 Physical Properties

Viscosity is the primary physical property of fuel oils affecting equipment operation and emissions. Viscous oils, No. 2 distillate and higher grades need to be atomized to form small droplets which can mix thoroughly with combustion air and burn efficiently and completely. The energy required to break up the oil in these droplets depends on the surface tension of the oil and the mean diameter of the desired droplet. Viscous residual oils have higher surface tensions, thus requiring more energy to achieve the same degree of atomization as a distillate oil. This is accomplished by heating the fuel to about 350 K (206°F) for No. 6 oil prior to atomization. In burners designed exclusively for kerosene and No. 1 distillate oil, the oil is generally not atomized but is prepared for burning solely by vaporization.

Three main methods of atomization are used in commercial boilers -- air, pressure and rotary atomization. Pressure atomization is used in about half of all commercial boilers, while air and rotary atomization methods are evenly divided among the remaining burner types (Reference 4-6). Steam atomization, which is prevalent with residual oil combustion, is not common in the small commercial size boilers.

The high-pressure atomizing gun oil burner is the most widely used residential heater distillate oil burner, accounting for over 90 percent of the total population (Reference 4-6). Low pressure and vertical rotary atomized burners are two other types of distillate oil-fired burners for residential heating.

Fuel oil viscosity and atomization methods have a significant effect on particulate and smoke emissions. A recent study of emissions from commercial hot water and steam boilers indicated that combustion of the heavier, more viscous fuels (i.e., lower API gravity) yielded higher emissions of smoke and filterable particulates under baseline operating conditions (Reference 4-39), as Figure 4-1 indicates. The heavier fuels also tend to have higher ash content, however the ash was found to be only partially responsible for the increase in particulate emissions.

Heavy viscous oils are also higher in molecular weight and have a lower percentage of hydrogen; they tend to form coke, especially with cyclic burner operation. This characteristic of residual oils makes for increased burner maintenance to clean carbon deposits. Carbon coking on

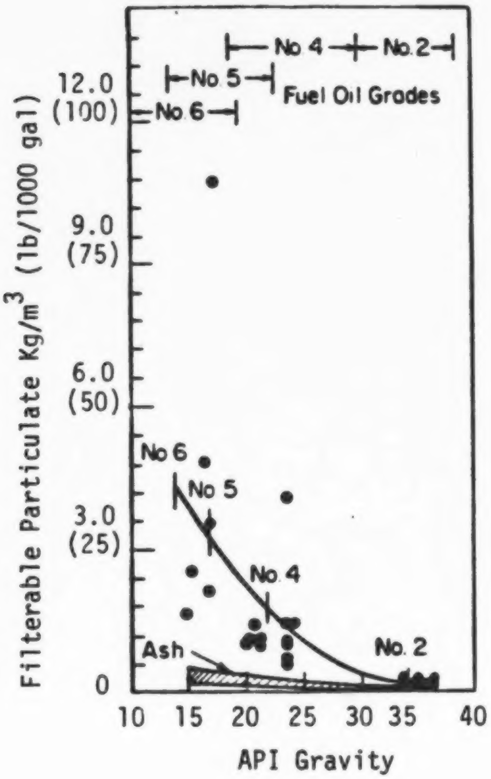

Figure 4-1. Effect of API gravity on particulate emissions (Reference 4-39).

the oil gun tip can lead to insufficient fuel-air mixing and consequent emissions of particulate and soot.

4.2.2.2 Chemical Properties

Sulfur and nitrogen concentrations in the fuel oil affect emissions of SO_x and NO_x respectively. Essentially all of the sulfur in the fuel oil converts to gaseous SO_2 and SO_3 during combustion. However, only 40 to 60 percent of the nitrogen in residual fuel oil is generally converted to NO_x (Reference 4-37). For low nitrogen content distillate oil the conversion can be as high as 100 percent. Heavier oils often contain more nitrogen and sulfur than distillate oils, contributing to higher NO_x and SO_x emission levels.

Certain constituents (impurities) present in most fuel oils are noncombustible and form residual ash. Most fuel oil ash results from contaminants present in the crude oil, with a minor fraction due to contamination occuring during handling or refining. Heavier fuels contain the most ash. The composition of fuel ash, particularly from residual oils, may include trace elements. Some of these elements are toxic and may adhere to aerosols emitted with combustion products. Distillate No. 2 oil contains very little ash and trace elements as compared with No. 6 residual oil. Because residential or commercial sources have generally low stack heights, the ground level concentration of these toxic elements in the immediate area of a residential or commercial heating plant burning residual oils may be significant.

In a study by the Langley Research Center on a commercial heating plant burning residual oil, it was found that toxic trace elements, Zn, Mo, Ag, Pb, and to a lesser extent Cd, tended to concentrate on small aerosols in the inhalable size range (Reference 4-14). The study concluded that combustion of residual oils in commercial heating equipment could cause toxic element concentration in the vicinity of the plant to be above safety levels established by the National Institute for Occupational Safety and Health (NIOSH). Therefore, either higher stacks for improved dispersion of these aerosols or combustion of cleaner distillate oils would be necessary to maintain low ambient trace element concentration.

4.2.3 Solid Fuels

Coal and wood are the principal solid fuels burned in combustion equipment with heat input capacity less than 2.9 MW (10×10^6 Btu/hr). Coal-fired warm air and hot water units represent only about 1 percent of the total residential heating equipment installed in 1976 (Reference 4-40). Coal for residential heating is either stoker or hand fed. In the commercial size sector, coal is more widely used contributing nearly 12 percent of the total installed commercial steam and hot water capacity (Reference 4-36). Coal combusted in this size category is all stoker fed. Combustor designs allow the use of a variety of coals. However, bituminous and anthracite are the primary coal types burned.

Equipment population statistics for wood-fired heaters and commercial boilers are not readily available. Two recent EPA test programs characterized emissions from wood-fired stoves and fireplaces. In addition control variables which affect these emissions were identified and investigated to the extent that they could be varied (References 4-28 and 4-29). The residential wood combustion source category will be reviewed separately in a subsequent effort of the NO_x EA program.

With the increasing scarcity and escalating cost of clean fuels, coal is being reconsidered as contributing a larger share of the fuel supply for commercial as well as residential space heating. Additionally, existing advanced designs of residential coal-fired equipment allow for a relatively automatic combustion of coal. However, the air pollution impact of widespread coal-fired residential heating will certainly be significant. Under adverse meteorological conditions, the air quality in residential areas heated with coal is expected to degrade significantly to the point that National Ambient Air Quality Standards (NAAQS) could be exceeded solely due to the residential equipment (Reference 4-41).

The following subsections highlight some of the physical and chemical characteristics of coal which affect emissions and equipment operation.

4.2.3.1 Physical Properties

Test results of two EPA-sponsored studies on coal combustion in residential size stokers indicate that physical properties of coals were the main parameters affecting the composition and quantity of air pollutants (References 4-25 and 4-26). Stoker operation and on-off cycling did not prove as significant on air pollutant emissions as did the varying physical properties of the coals tested.

The free swelling index, volatile content, and coal size are the primary coal properties that affect the emissions of particulates, smoke and polynuclear organic material (POM). The effect of coal ash content on these emissions was found to be of secondary importance.

The free swelling index is a measure of the caking property of coals. High volatile bituminous coals have high free swelling index and thus, they tend to cake on stoker bed and form large clinkers. These clinkers do not permit a uniform distribution of combustion air which leads to higher emissions of particulate (smoke), CO, hydrocarbons and POM.

Figure 4-2 shows the effect of the free swelling index on particulate emissions measured in two test programs on residential stoker-fed heaters. Anthracite and western subbituminous coals with free swelling indices less than 1 did not cake, permitting a more uniform air

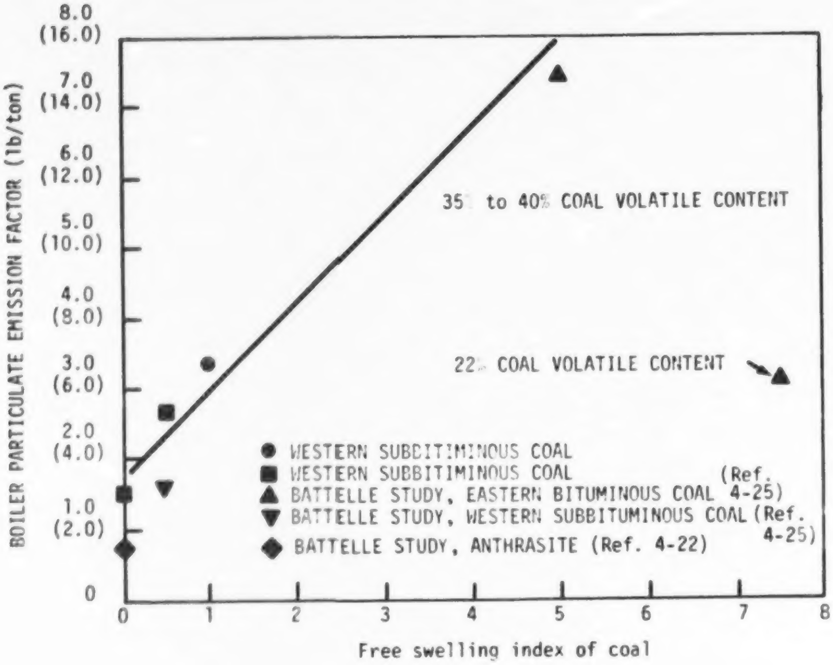

Figure 4-2. Effect of free swelling index on boiler particulate emissions (Reference 4-26).

distribution throughout the bed. Particulate emissions averaged 10 to 30 percent of particulate emission levels from bituminous coals.

The high volatile content of bituminous coal also tended to produce high levels of particulate, smoke, and POM emissions during tests on residential units. POM levels were highest during the "off" portion of the cycle when the low bed temperature and lack of combustion air did not permit combustion of tars released from the coal bed. Figure 4-3 shows the effect of volatile content on particulate emissions. Anthracite, shown in Figure 4-2, with a volatile content of about 4 percent registered the lowest particulate emissions, 0.15 g/kg coal (0.3 lb/ton coal). High volatile bituminous coals emitted the highest particulate levels. High particulate emissions were also accompanied by higher smoke and POM emissions. Coal size and ash content have a less pronounced effect on particulate, smoke and POM emission from residential size heaters. However, a large amount of fines in the coal tended to increase particulate emissions during the "on" cycle. This was attributed to the combustion air carrying the light particles to the flue.

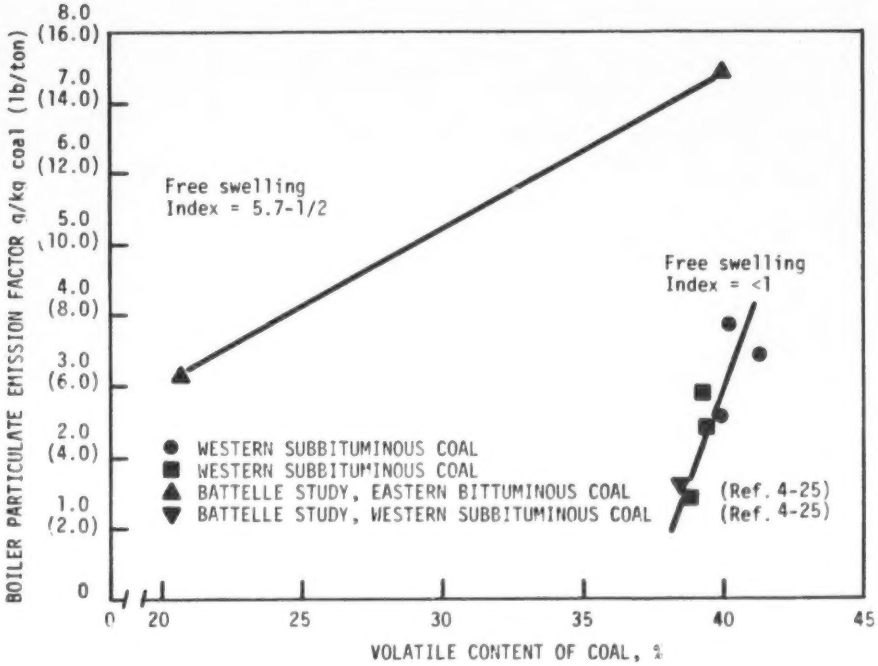

Figure 4-3. Effect of coal volatile content on boiler particulate emissions (Reference 4-26).

These emission levels indicate that anthracite is the most desirable coal type for residential and small commercial heating equipment. However, availability of anthracite is limited, while bituminous coal is much more abundant and is indigenous to many eastern states. Western subbituminous coals and processed lignitic (smokeless) coals were investigated as alternatives to the combustion of bituminous coals in residential furnaces and boilers. As indicated in Figures 4-2 and 4-3 these coals have generally lower free swelling indices but, except for the smokeless coal, also have about the same amount of volatile matter as bituminous coals. Overall, subbituminous coals were found to be less polluting than bituminous coals and thus, in the absence of anthracite, are more desirable as fuels for residential and commercial heating equipment (Reference 4-23).

4.2.3.2 Chemical Properties

Coal contains a significant amount of elemental metals of which a portion are released to the atmosphere during combustion. The rest is removed from the boiler with the bottom ash. De Angelis and Reznik reported that in general less than 10 percent of trace metal species in the coal find their way to the atmosphere through the stack, however high volatile mercury and selenium in the flue gas measured over 50 percent of that introduced with the coal (Reference 4-25). In another study, Surprenant, et al., reported that at least 1 percent of the less volatile trace metallic elements were released to the atmosphere from residential units (Reference 4-42). These trace elements generally include lead, cadmium, arsenic, selenium and zinc, all of which are of significant environmental concern. Mercury, which is highly volatile, leaves the boiler in vapor form.

Trace elements remaining in the bottom ash also constitute an environmental concern. Some of these elements, aluminum, calcium, barium, sodium, silicon and strontium, are leached by rainfall and can enter potable water supplies.

With wood combustion in residential stoves and fireplaces, high resin content combined with high moisture content of unseasoned (green) pine wood was attributed with high particulate, condensible organic and polycyclic organic material (POM) emissions compared with combustion of drier and harder woods (Reference 4-28). Resinous material content and chemical composition of soft woods, such as pine, may then have a direct impact on the organic emission characteristics from wood combustion in residential systems.

4.3 PRODUCT CHARACTERIZATION

The principal products of residential and commercial combustion equipment are warm air, hot water or steam. Warm air furnaces and hot water boilers are generally smaller than 0.1 MW (400,000 Btu/hr) heat input capacity. Steam units are a more popular equipment category with heat capacity above 0.4 MW (1.5×10^6 Btu/hr). For warm air applications, hot water or steam can be used as an intermediate fluid to exchange heat with a forced air circulating system. Steam from small commercial size units is also used in industrial process plants.

As discussed in Section 3, direct warm air systems exhaust the flue gas directly into the heated air for maximum thermal efficiency. Direct heating, however, has the disadvantages of creating increased ambient levels of NO_x, CO and HC in the space being heated. These indoor areas require good ventilation which then reduces the effectiveness of the direct heating system.

4.4 NO_x FORMATION

Two mechanisms have been identified as responsible for NO_x formation during the combustion process: thermal NO_x formation and fuel NO_x formation. The following subsections summarize these formation concepts. A more extensive discussion is given in Reference 4-43.

4.4.1 Thermal NO_x Formation

Thermal NO_x results from the thermal fixation of molecular nitrogen and oxygen in the combustion air. The detailed chemical mechanism by which molecular nitrogen in the combustion air is converted to nitric oxide is not fully understood. In practical combustion equipment, particularly for liquid or solid fuels, the kinetics of the N_2-O_2 system are coupled to the kinetics of hydrocarbon oxidation and both are influenced, if not dominated, by effects of turbulent mixing in the flame zone. It is, however, generally accepted that thermal NO_x forms at high temperatures in an excess of O_2. For natural gas and light distillate oil firing, nearly all NO_x emissions result from thermal fixation. With residual oil and coal the contribution from fuel-bound nitrogen can be significant and may even predominate.

4.4.2 Fuel NO_x Formation

Fuel NO_x derives from the oxidation of the organically bound nitrogen present in certain fuels such as residual and distillate oils. Fuel NO_x emissions are dependent on the nitrogen content of the fuel as well as on combustion conditions. Fuel NO_x formation is strongly affected by the rate of mixing of the fuel and airstream in general, and by local oxygen concentration in particular.

Fortunately, with high nitrogen fuels only a portion of the fuel bound nitrogen is converted to NO_x. Barrett and Locklin investigated the contribution of fuel N to total NO_x emissions from oil-fired commercial boilers (Reference 4-39). Their results are summarized in Figure 4-4. As indicated, the contribution of thermal NO_x to total NO_x emissions is approximately 100 ppm. Total NO_x emissions steadily increase as the nitrogen content of the fuel increases. However, the fractional conversion of fuel nitrogen decreases as the fuel nitrogen content increases. Commonly reported conversion rates range from 40 to 60 percent for residual oils and to nearly 100 percent for distillate oils (very low nitrogen content).

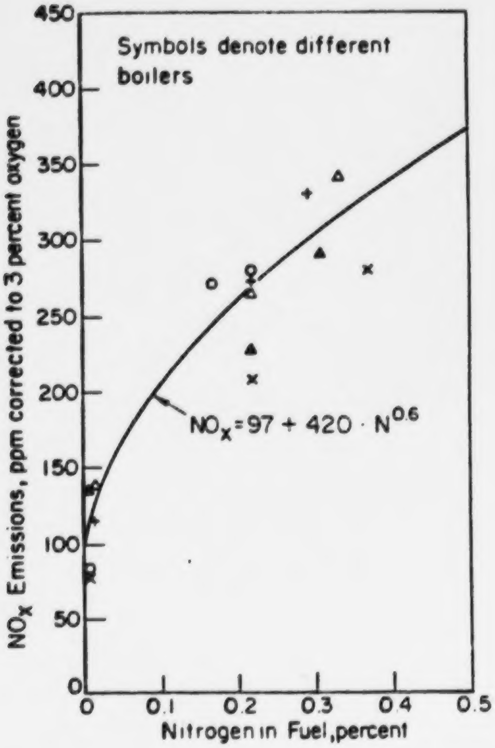

Figure 4-4. Contribution of nitrogen in fuel oil to total NO_x emissions from commercial boilers (Reference 4-39).

Fuel nitrogen conversion to NO_x when burning coal can range from 20 to 60 percent depending on the coal type and percent nitrogen in the fuel (Reference 4-44). In addition, this conversion is highly dependent on the fuel-air ratio. Since coal in commercial and residential equipment is generally burned in stokers with high excess air levels, conversion of fuel nitrogen to NO_x is high.

4.5 EMISSION CHARACTERIZATION

Emissions from natural gas-fired residential and commercial combustion sources include primarily NO_x, CO and HC. When fuel oil or coal is burned, smoke, particulate and SO_x are also emitted. The levels of NO_x, CO and HC from oil and coal combustion are usually higher than those from gas combustion. Figures 4-5 and 4-6 illustrate general trends of steady-state smoke and gaseous emissions from oil-fired residential heaters and commercial boilers, respectively, as they are influenced by

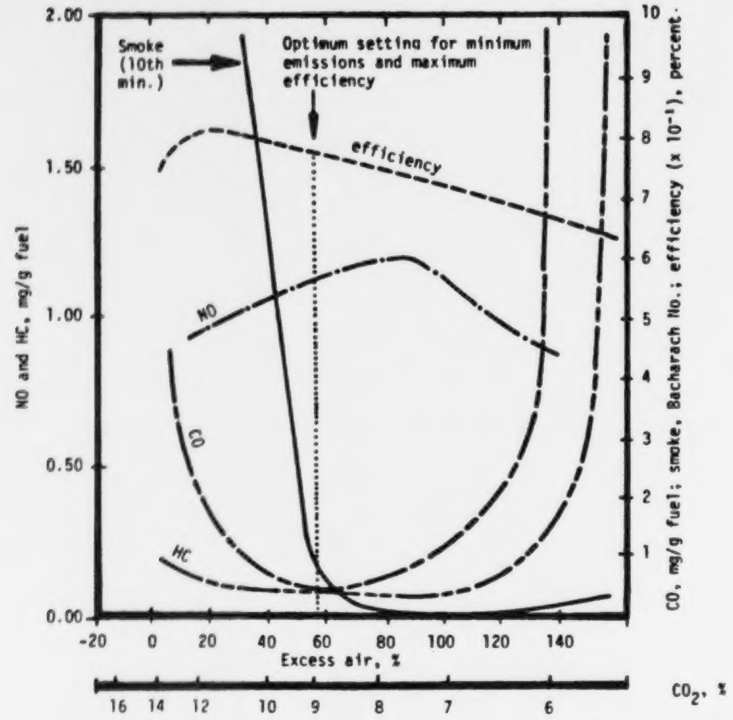

Figure 4-5. General trend of smoke, gaseous emissions, and efficiency versus stoichiometric ratio for a residential oil burner (Reference 4-7).

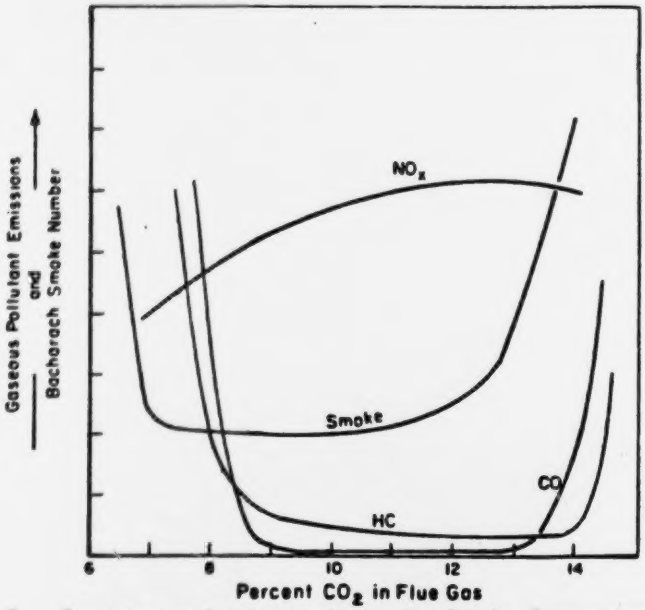

Figure 4-6. Gaseous emissions characteristic for a typical commercial boiler as influenced by combustion air setting (Reference 4-45).

combustion air settings. For both equipment types the operating setting corresponding to lowest emissions of CO, HC, and smoke coincides with high NO_x levels. As the excess air is reduced from the theoretical setting, concentrations of CO, HC and smoke increase because of lack of oxygen in the flame and reduced turbulent mixing which leads to incomplete combustion. At very high excess air levels, these emissions can also increase due to the excessive combustion air which cools the flame also resulting in incomplete combustion.

One of the major factors contributing to high combustible emissions, particularly in domestic burners, is the transient operating mode. The on-off cycle is a dominant characteristic of warm air furnaces, and its importance as a cause of increased emissions has been well documented (References 4-6 and 4-7). A typical furnace cycle is shown in Figure 4-7. The burner is ignited at a point off the chart and, after a minute or so, the blower starts circulating air over the heat exchanger. Four minutes later the burner flame is extinguished, and about 5 minutes after that the blower stops. Investigations on a model residential heating system indicated that the sizeable peak emissions measured during ignition and shutdown can account for most of the total combustible emissions. Figure 4-8 shows qualitative emission traces from an oil burner during a typical cycle. CO and HC emissions peak at ignition and shutoff. HC concentration drops to insignificant levels between the peaks, while CO emissions tend to flatten out at a measurable level. Particulate emissions continuously taper off after the ignition-induced peak, whereas NO emissions first rise rapidly for a short period and then continue to rise at a more moderate rate as the combustion chamber temperature increases. The operating time of most domestic burners seemingly is not long enough for NO to reach equilibrium levels.

The transient emissions are caused mainly by variations in the combustion chamber temperature. At ignition, a cold refractory will not assist complete combustion and, therefore, peaks of CO, HC, and smoke can occur. In addition to the cold refractory, wear and tear of the oil pump can cause poor shut-off performance, hence high smoke and combustible emissions. This problem can be minimized by the use of solenoid valves in the fuel tube (delayed on-instant off), the placement of this valve nearer to the burner tip, and the use of smaller diameter tubes.

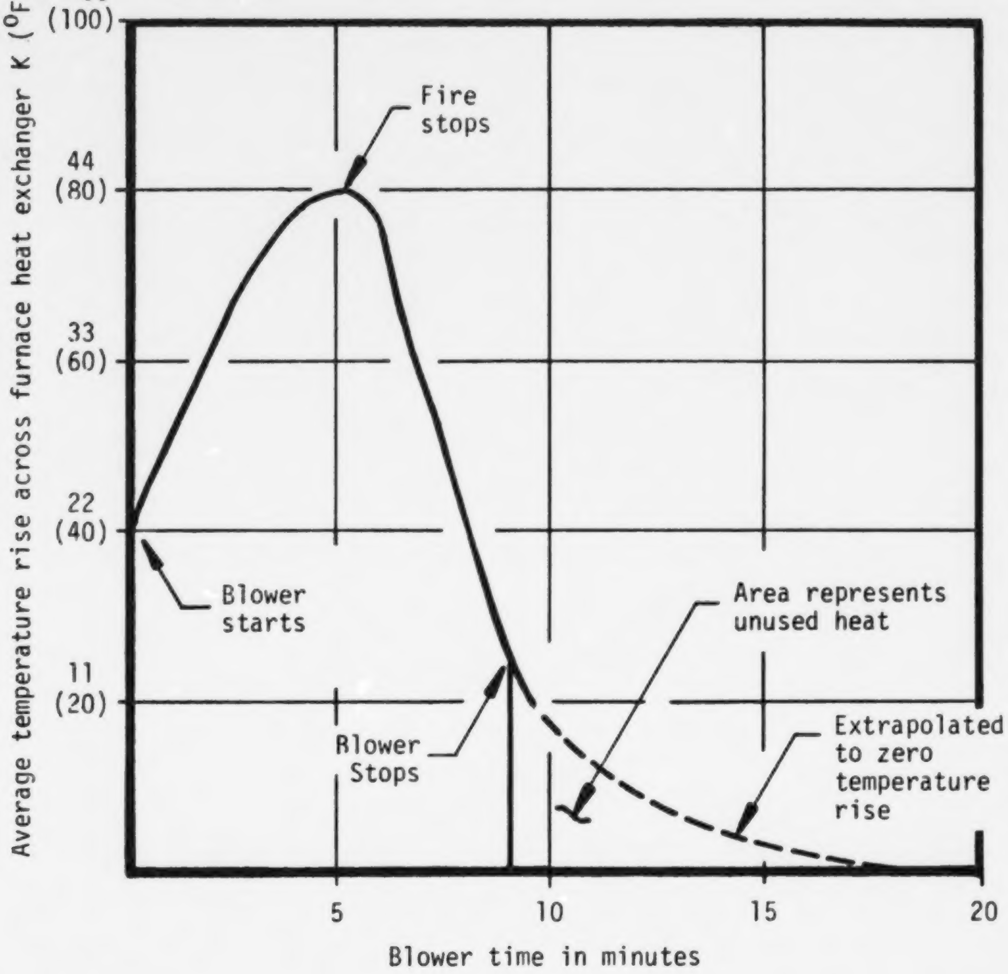

Figure 4-7. Temperature rise across an oil-fired warm air furnace heat exchanger during a typical cycle.

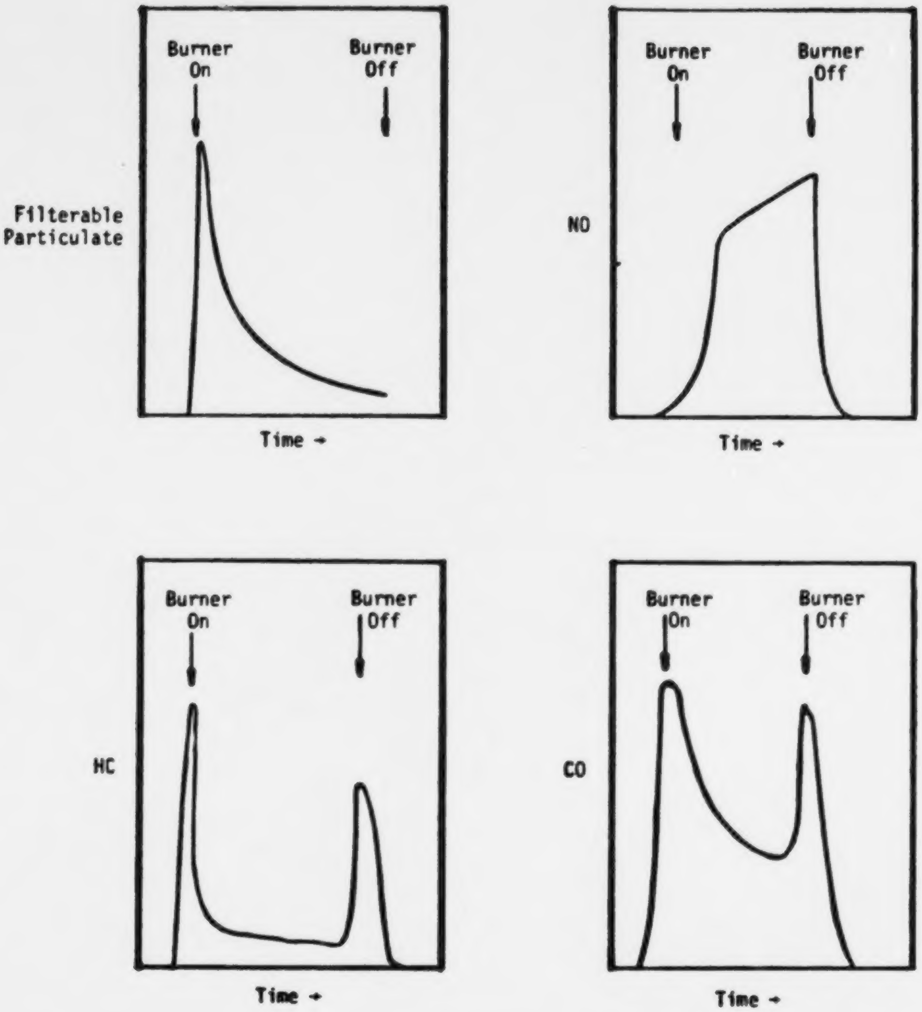

Figure 4-8. Characteristic emissions of oil burners during one complete cycle (Reference 4-7).

In general, with the exception of SO_x emissions which depend entirely on the sulfur content of the fuel, all other criteria pollutants are primarily a function of burner nozzle type, combustion chamber shape and material, and operating practice. The following subsections highlight some of these parameters and how each affects the various criteria pollutant emissions.

4.5.1 Nitric Oxide Emissions

Nitric oxide production from fuel oil combustion is highest in high temperature turbulent diffusion flames rich in excess oxygen. NO_x emissions from residential heaters, which burn primarily natural gas and distillate oil that is relatively low in fuel nitrogen content, are due to thermal NO_x. The oxidation of molecular nitrogen in the combustion air depends on residence time and temperature. The higher temperatures and long residence times promote production of thermal NO. Fuel/air ratios have less effect on thermal NO production than on fuel nitrogen conversion, which is highly affected by excess oxygen availability during pyrolysis of fuel nitrogen compounds.

4.5.2 Carbon Monoxide and Hydrocarbon Emissions

Both CO and HC are products of incomplete combustion. Steady-state and cyclic combustible emissions in small residential and commercial sources have been attributed to excessive firing rate (or input rate) and lack of scheduled maintenance. A field survey concluded that a large majority of oil-fired residential heating systems have an excessive firing rate which leads to high stack losses and reduced seasonal efficiency (Reference 4-46). Oversized residential heaters cycle more frequently because the heating load is met quickly and the furnace shuts down. During the ignition and shutdown periods, emissions of CO and HC are high because of flame quenching from the cold wall. A reduction in burner capacity (i.e., lower firing rate) reduces these emissions significantly and increases the overall cycle efficiency of the units. Residential burner performance can usually degrade with time; if so, the furnace emits unneccessarily high levels of combustible CO and HC. Improper burner adjustment may cause flame impingement or reduced stoichiometry which lead to incomplete combustion. Scheduled burner maintenance by skilled servicemen remedies this problem.

4.5.3 Smoke and Particulate Emissions

Smoke and particulates from oil-fired residential and commercial units consist primarily of carbon particulate (soot) which is a product of incomplete combustion. These emissions increase with short furnace residence time and cold wall furnace effect. Short furnace residence time is characteristic of small size combustion chambers of conventional residential heaters. Larger fireboxes can help reduce particulate emissions by as much as one-fourth (Reference 4-7). Combustion chambers of domestic oil burners are usually made of hard refractory, ceramic felt material or steel. The temperature of a refractory lined chamber reaches steady state with combustion gases faster and retain the heat longer than steel chambers. Therefore, residential oil burners with ceramic lined chambers emit lower particulate and smoke than do steel chambers. During the time in which chamber temperature is low, however, excess air levels must be increased to counteract the poor combustion due to low temperature. Since it has not been practical to allow for altering the amount of excess air during a heating cycle, the initial high air level is maintained throughout, resulting in low thermal efficiency.

4.5.4 Emission Factors and Emission Inventory

Emission factors together with fuel consumption were used to calculate total 1977 emissions from combustion sources having heat input capacity less than 2.9 MW (10 x 10^6 Btu/hr) (Reference 4-47). As discussed earlier, this site category also includes a significant number of boiler equipment used in industry in addition to those used for residential and commercial heating. Fuel consumption and emissions in Table 4-3 are presented by end use. As indicated, fuel consumption data for residential systems were obtained directly from the Department of Energy (Reference 4-48). Fuel consumption for the industrial and commercial sources with heat input capacity less than 2.9 MW (10 x 10^6 Btu/hr) was calculated using equipment installed capacity and load factors estimated in a recent EPA-sponsored study (Reference 4-36).

Gas- and distillate oil-fired residential systems contributed the most to total NO_x emissions from these sources. This is due to the fuel consumption for residential heating which accounted for nearly 65 percent of the total fuel consumption.

TABLE 4-3. ESTIMATED 1977 AIR POLLUTANT EMISSIONS FROM STATIONARY FUEL COMBUSTION SOURCES WITH HEAT CAPACITY LESS THAN 2.9 MW (10 x 10^6 Btu/hr)[a]

Sector	Equipment	Fuel	Total Capacity MW (10^6 Btu/hr)	Fuel[b] Consumption EJ (Quads)	Air Pollutant Emissions Gg (10^3 tons)				
					NO_x	CO	HC	Particulates	SO_x
Residential[c]	Warm air central furnaces	Natural gas	--	1.876[c] (1.979)	65.7 (72.5)	19.0 (20.9)	6.40 (7.10)	7.50 (8.27)	0.49 (0.54)
		Distillate oil	--	1.354[c] (1.428)	33.8 (37.3)	33.8 (37.3)	6.40 (7.06)	10.3 (11.4)	146 (161)
	Warm air space heaters	Natural gas	--	0.57[c] (0.60)	19.9 (21.9)	5.7 (6.3)	1.94 (2.14)	2.30 (2.54)	0.15 (0.17)
		Distillate oil	--	0.42[c] (0.44)	10.5 (11.6)	10.5 (11.6)	1.97 (2.17)	3.20 (3.53)	45.4 (50.1)
Residential and Commercial	Miscellaneous combustion	Natural gas	--	1.524[c] (1.608)	53.3 (58.8)	15.2 (16.8)	5.20 (5.73)	6.10 (6.73)	0.40 (0.44)
		Distillate oil	--	0.926[c] (0.977)	27.4 (30.2)	27.4 (30.2)	5.15 (5.68)	8.33 (9.19)	118.4 (130.6)
	Steam and hot water heaters	Natural gas	--	2.1[c] (2.2)	82.8 (91.3)	17.8 (19.6)	4.76 (5.25)	16.6 (18.3)	0.62 0.68
		Distillate oil	--	1.4[c] (1.5)	77.9 (85.9)	41.7 (46.0)	13.4 (14.8)	10.6 (11.7)	150.2 (165.6)
		Residual oil	--	0.11[c] (0.12)	17.5 (19.3)	1.64 (1.81)	2.74 (3.02)	9.09 (10.0)	52.6 (58.0)
		Coal	--	0.043[c] (0.045)	7.1 (7.8)	7.53 (8.30)	2.12 (2.34)	150.2 (165.6)	30.7 (33.8)

[a] Based on data from References 4-36, 4-47, and 4-48.
[b] EJ = 10^{18} Joules = 0.948 Quads = 0.948 x 10^{15} Btu
[c] Fuel consumption for residential units was obtained from Department of Energy (Reference 4-48).

TABLE 4-3. (Concluded)

Sector	Equipment	Fuel	Total Capacity MW (10^6 Btu/hr)	Fuel[b] Consumption EJ (Quads)	Air Pollutant Emissions Gg (10^3 tons)				
					NO_x	CO	HC	Particulates	SO_x
Commercial and Industrial	Cast iron boilers	Natural gas	143,520 (489,495)	1.8 (1.9)	91.7 (101.1)	35.3 (38.9)	4.06 (4.48)	6.88 (7.59)	0.53 (0.58)
		Distillate oil	33,730 (115,041)	0.35 (0.37)	23.7 (26.1)	0.56 (0.61)	3.34 (3.68)	4.18 (4.61)	37.6 (41.5)
		Residual oil	53,790 (183,456)	0.47 (0.50)	84.6 (93.3)	0.66 (0.73)	11.8 (13.8)	13.2 (14.6)	225.6 (248.8)
		Coal	31,590 (107,742)	0.097 (1.0)	14.6 (16.1)	21.3 (23.5)	5.53 (6.10)	314.3 (346.6)	110.6 (122.0)
	Watertube boilers	Natural gas	5,770 (19,679)	0.053 (0.056)	3.16 (3.5)	1.06 (1.17)	0.18 (0.20)	0.05 (0.05)	0.02 (0.02)
		Distillate oil	4,490 (15,313)	0.021 (0.023)	1.18 (1.3)	0.06 (0.07)	0.01 (0.01)	0.18 (0.20)	3.27 (3.61)
		Residual oil	5,240 (17,872)	0.015 (0.016)	2.38 (2.6)	0.02 (0.02)	0.07 (0.08)	0.42 (0.46)	6.70 (7.39)
		Coal	1,900 (6,480)	0.012 (0.013)	3.0 (3.3)	0.91 (1.00)	0.19 (0.21)	23.5 (25.9)	16.0 (17.6)
	Firetube boilers	Natural gas	79,090 (269,748)	1.358 (1.433)	31.0 (34.2)	15.2 (16.8)	1.75 (1.93)	3.02 (3.33)	0.23 (0.25)
		Distillate oil	31,530 (107,538)	0.37 (0.39)	12.8 (14.1)	0.34 (0.38)	2.05 (2.26)	2.57 (2.83)	18.7 (20.6)
		Residual oil	48,200 (164,393)	0.354 (0.374)	30.7 (33.9)	0.29 (0.32)	5.12 (5.65)	5.73 (6.32)	92.1 (101.61)
		Coal	14,420 (49,181)	0.11 (0.116)	14.1 (15.6)	5.40 (5.95)	3.40 (3.75)	130.0 (143.4)	91.8 (101.2)
TOTAL	All equipment	All fuels	--	15.22 (16.97)	708.8 (781.6)	261.4 (288.3)	87.6 (96.6)	728.3 (803.1)	1,148.1 (1,266.0)

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SECTION 5
PERFORMANCE AND COST OF CONTROLS

This section discusses the performance and cost of various control options applicable to gas-, oil-, and coal-fired residential systems. Controls for each of these equipment categories are discussed in three separate sections according to the fuel burned. Control technology developed specifically for NO_x emission reduction are also highlighted and discussed separately from controls specifically developed for other pollutants. Published costs and energy considerations of these controls are also summarized for each fuel category. All costs are in 1978 dollars unless otherwise indicated. Discussion of emission control technology for commercial steam and hot water boilers is limited because of lack of investigative efforts in this area. However, technology transfer from the small industrial boiler sector is discussed.

5.1 EMISSION CONTROL ALTERNATIVES FOR GAS-FIRED RESIDENTIAL SYSTEMS

NO_x emission control techniques for gas-fired residential furnaces have been investigated since the early 1970's by the American Gas Association Laboratories (AGAL), the Gas Appliance Manufacturers Association (GAMA), and the EPA. Early work by AGAL quantified the variation of NO_x, CO, and hydrocarbon emissions from gas-fired residential units according to burner type and firebox design. This work showed that multiport gas burners were found to emit approximately 25 percent higher NO_x than single port burners (Reference 5-1). This was attributed to a compact, intense flame front with the multiport burners which promotes NO_x formation. Single port burners have larger burner flame volumes which result in fewer high intensity temperature regions to promote NO_x formation (Reference 5-2). Some observations were also made by AGAL on the effect of primary air setting (primary aeration) and heat exchanger material on NO_x emissions. These effects were generally found to be less important than burner design (Reference 5-1).

5.1.1 Nitric Oxide Control

Because NO_x emissions from combustion of natural gas are from thermal NO formation, control techniques are aimed at controlling flame temperature, residence time, and oxygen availability at the high temperature flame region. Five major NO_x control options have been identified for residential gas-fired warm air furnaces and hydronic boilers. These control options are:

- Radiant screens
- Secondary air baffles
- Modulating combustion cycle
- Heat transfer module (HTM)
- Surface combustion burner (Bratko type)
- Catalytic combustors

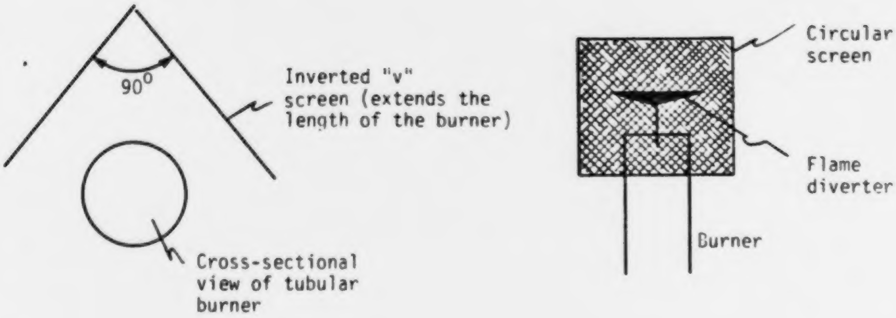
The following subsections discuss the NO_x reduction performance, applicability and cost of each of these control options.

5.1.1.1 Radiant Screens

Himmel and De Werth of AGA originally reported that infrared gas burners emit lower nitric oxides than conventional type burners (Reference 5-2). Incandescent radiant screens in a natural gas flame tend to approach the level of infrared burners by radiating heat to the surroundings and cooling the flame. An inverted "V" screen was placed above the tubular multiport burner and extended the length of the burner. For a single port upshot burner, a circular screen was placed around the burner. Both arrangements are illustrated schematically in Figure 5-1.

Table 5-1 summarizes the performance of radiant screens on three warm air furnaces. As shown, the NO_x was reduced from 36 to 76 percent with an average reduction of 58 percent. The radiant screen performance was more significant with tubular multiport burners. Similar results were obtained in other warm air furnaces when burners were modified by installation of radiant screens. In general, this control technique was also found to increase steady-state furnace efficiency slightly due to increased flame and burner radiation.

AGAL, however, warns that the radiant screen concept, although workable, needs further investigation to assess its durability in the flame, its potential deterioration or deformation and overall safety. Some concerns were also published in a recent GAMA report in response to


90^0
Inverted "v" screen (extends the length of the burner)
Cross-sectional view of tubular burner
Circular screen
Flame diverter
Burner

(a)
For multiport tubular burner

(b)
For single port upshot burner

Figure 5-1. General arrangements of screens for gas-fired residential burners (based on illustrations from Reference 5-1).

TABLE 5-1. EFFECT ON CO AND NO_x EMISSION OF PLACING RADIANT SCREEN IN BURNER FLAME (Reference 5-1)

Unit	Sample CO_2 Percent	Flue Gas Concentration ppm, (0% O_2)				NO_x Percent Change
		CO	NO	NO_2	NO_x	
FAF 23 -- Tubular Multiport						
No Screen	8.50	14	104.9	0	104.9	
Screen	8.30	15	23.4	1.6	25.0	-76%
FAF 25 -- Tubular Multiport						
No Screen	7.70	8	76.7	3.7	80.5	
Screen	7.75	11	21.5	3.4	24.9	-69%
FAF 9 -- Single Port Upshot with Flame Spreader						
No Screen	4.05	15	61.3	1.6	62.9	
Screen	4.05	44	37.3	3.0	40.3	-36%

FAF = Forced Air Furnace

the recommendations by the California Air Resources Board (CARB) for the potential commercial application of radiant screens to control NO_x from warm air furnaces (References 5-3 and 5-4). Some of the potential problems presented by GAMA included sensitivity of performance to screen location, effect on CO emissions, and deterioration.

The screen design and location in or around the burner are critical to its performance. Figure 5-2 illustrates how NO_x reductions can drastically vary with location of the screen. This sensitivity precludes retrofit application to existing units unless they are made by skilled service appliance personnel. GAMA also indicated that CO emissions can increase significantly with the application of screens, even with furnace manufacturer-suggested air settings. Furthermore, if these air settings were to become misadjusted during installation or servicing, unacceptable CO emissions would result. Test results by GAMA summarized in Table 5-2 show that CO increased above 1000 ppm with natural gas and a liquified natural gas. With regard to screen durability it is expected that the cycling operation of the residential equipment would impose numerous thermal shocks to the screens which could eventually deform or break. Screen deterioration could lead to loss in performance and/or excessive CO and HC emissions.

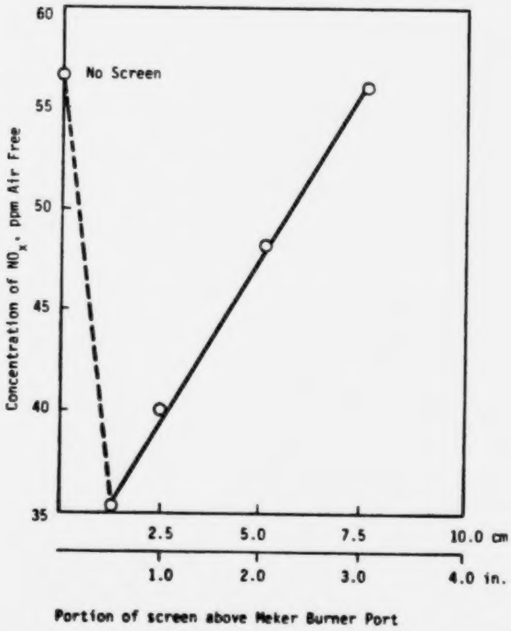


Figure 5-2. Effect on NO_x emissions of placing a screen in the flame of a Meker Type burner (Reference 5-3).

TABLE 5-2. EFFECT OF A RADIATING SCREEN FROM A FURNACE OPERATED ON CLEVELAND NATURAL AND ALGERIAN LNG (Reference 5-3)

Test Conditions	Steady State Flue Gas Concentration, ppm Air Free			
	Cleveland Natural Gas		Algerian Gas	
	NO_x	CO	NO_x	CO
A -- Unmodified Burners				
-- Manufacturer's recommended setting	70	10	65	10
-- "Hard" flame setting	72	109	--	--
-- "Soft" flame setting	63	693	--	--
B -- Inverted "V" 10 x 10 mesh inconel screen added to burners with manufacturers suggested air shutter setting	31	30	28	480
C -- Same as "B" except air shutters wide open (hard flame)	33	1000+	28	1000+
D -- Same as "B" except air shutters closed (soft flame)	36	1000+	32	1000+

5.1.1.2 Secondary Air Baffles

The effect of the secondary air baffle is to control secondary airflow into the flame front. Decreasing excess oxygen availability at peak temperatures with reductions in secondary airflow was found to reduce NO_x emissions on the order of 10 to 40 percent (Reference 5-1). However, NO_x reductions without increases in CO emissions were generally limited to about 15 percent. The effect of the secondary air baffle was found to be sensitive to its geometry and positioning with respect to the burner port. Therefore, concerns expressed by GAMA with this technique are similar to those pointed out for the radiant screen control option.

Furthermore, it is not clear whether the secondary air baffles can be applied to all types of residential burner designs.

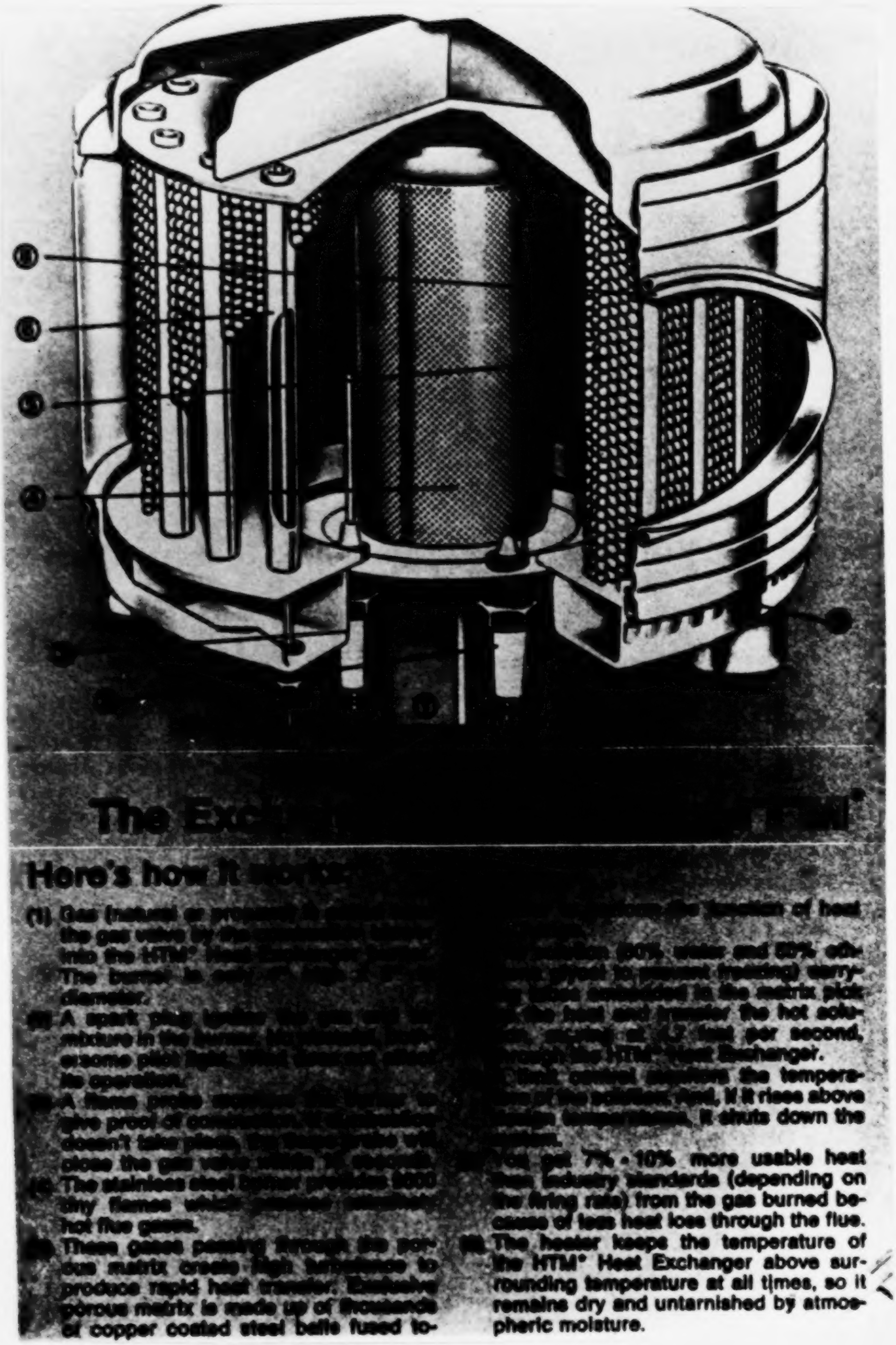
5.1.1.3 Modulating Furnace

The modulating furnace also tested by AGAL is a commercially available residential heater design. The furnace differs from conventional units in that the firing rate is altered to respond to the heating load demand instead of cycling on and off. In this manner, the furnace is essentially derated, yielding a cooler flame which apparently leads to lower NO_x emissions. The reported NO_x emission factor for this furnace design is 24.9 ng/J (0.058 lb/10^6 Btu) (Reference 5-1). This corresponds to about a 40 percent reduction from emission levels of conventional furnaces.

GAMA indicated that this reduction in NO_x mass emission achieved with the modulating furnace was due to the single-port inshot burner type used originally rather than the reduced heat input rate as indicated by AGAL (Reference 5-3). However, it can be speculated that elimination of the on-off cycle should reduce combustible emissions because CO and UHC emission peaks characteristic of ignition and shutdown would decrease. However, no emission data are available to substantiate this hypothesis.

5.1.1.4 Heat Transfer Module (HTM)

The HTM by Amana shown in Figure 5-3 has been commercially available for about 6 years. The design includes a perforated burner located in the center. The natural gas mixes with air through the many holes of the burner and burns at the burner surface. The heat is transferred to an intermediate glycol solution in small tubes imbedded in a close fitted fin arrangement surrounding the burner. The glycol then transfers heat to room air. The HTM is used for both heating and air conditioning and is designed for outdoor installations. One additional important feature of the HTM furnace is the lack of a pilot. The flame is spark ignited instead of using a pilot flame. Thus seasonal fuel consumption is reduced compared with pilot ignition furnaces. NO_x emissions reported by AGAL averaged 7.74 ng/J (0.018 lb/10^6 Btu) which corresponds to an emission reduction of about 80 percent from conventional warm air furnace design (Reference 5-1).



The Exc[illegible] HTM®

Here's how it [illegible]

(1) Gas (natural or propane) [illegible] the gas valve by [illegible] into the HTM® Heat [illegible] The burner is [illegible] diameter.

A spark plug ignites the gas and air mixture in the burner [illegible] or some pilot light [illegible] its operation.

A flame probe [illegible] to give proof of com[illegible] doesn't take place, the flame probe will close the gas valve [illegible]

The stainless steel burner provides 1000 tiny flames which [illegible] hot flue gases.

These gases passing through the porous matrix create high turbulence to produce rapid heat transfer. Exclusive porous matrix is made up of thousands of copper coated steel balls fused to-

[illegible] the function of heat [illegible]

[illegible] solution (50% water and 50% ethylene glycol to prevent freezing) carry[illegible] tubes embedded in the matrix pick [illegible] the heat and transfer the hot solution, moving at 4.7 feet per second, through the HTM® Heat Exchanger.

[illegible] limit control monitors the temperature of the solution fluid. If it rises above design temperatures, it shuts down the [illegible]

You get 7% - 10% more usable heat than industry standards (depending on the firing rate) from the gas burned because of less heat loss through the flue.

The heater keeps the temperature of the HTM® Heat Exchanger above surrounding temperature at all times, so it remains dry and untarnished by atmospheric moisture.

Figure 5-3. Amana Heat Transfer Module (HTM)

Recently, the HTM combustor has been tested by the Southern California Gas Company. Preliminary results indicate that the Amana design might not be capable of the 80 percent NO_x reduction reported by AGAL. Follow-up measurements are scheduled for the near future to verify the validity of this new finding (Reference 5-5).

5.1.1.5 Surface Combustion Burner

A schematic of the surface combustion burner by Bratko is illustrated in Figure 5-4. This burner employs surface combustion of premixed natural gas and air on a refractory porous material. The burner becomes incandescent and radiates heat to an air-cooled firebox. In this manner, the combustion zone is maintained below about 1,250 K (1,790^{0}F). NO_x emissions of about 7 ng/J (0.016 lb/10^6 Btu), corresponding to over 80 percent reduction, have been reported with a prototype furnace using the surface combustor (Reference 5-6). The furnace maintains steady-state thermal efficiencies of 80 percent or more by operating with only 10 percent excess air.

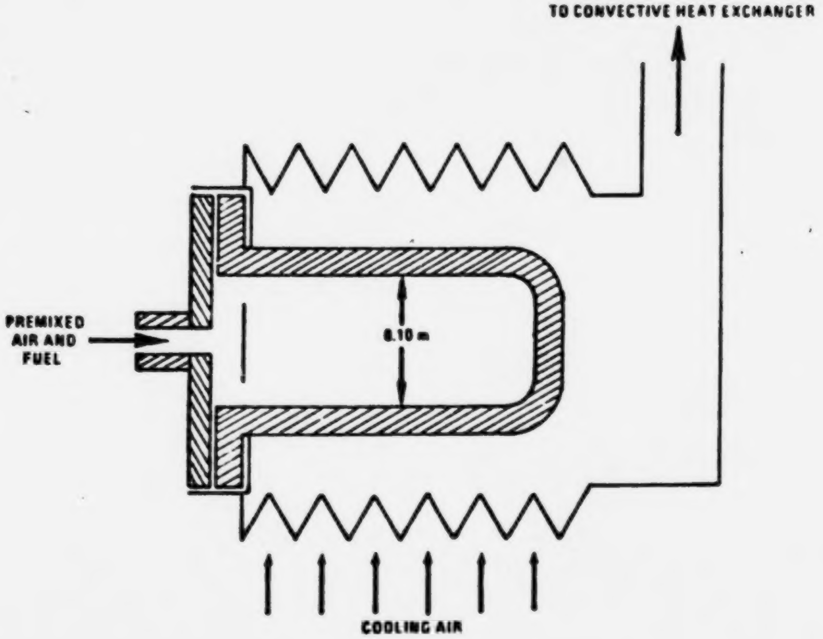


Figure 5-4. Schematic of the Bratko Burner (Reference 5-6).

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The refractory surface combustion concept is not a new one. In fact, some commercial direct fired heaters use this refractory burner (refer to Section 3.2.2 for discussion). NO_x emissions data from those commercial units are, however, not available.

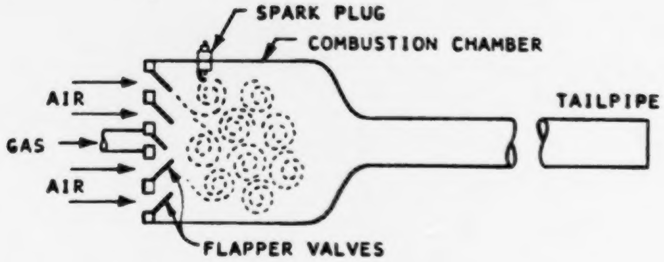
5.1.1.6 Pulse Combustors

The concept of pulse combustion has been known since the turn of the century. This concept, illustrated in Figure 5-5, involves combustion in a chamber fitted at one end with mechanical flapper valves and at the other end with an open exhaust pipe. The fuel (natural gas, propane or light distillate) is introduced with the air through the flapper valves. The mixture entering the chamber is ignited with an electric spark plug. the resulting pressure of combustion closes the flapper valves and forces the product gases through the exhaust pipe. The exhaust products leaving the chamber in time create a negative pressure, which causes the valves to open, in a manner similar to an internal combustion engine, thus repeating the cycle. The most extensive application of pulse combustion was in the German VI "buzz bomb" during World War II.

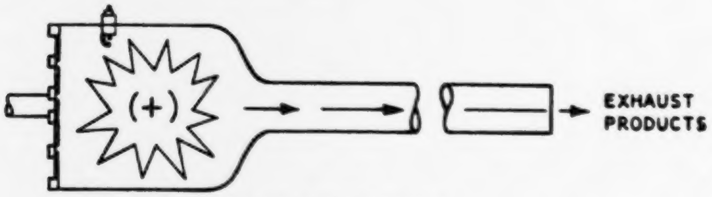
Application of the mechanical valved pulse combustor for home heating has been studied since the early 1950's. The simplicity of construction, compactness, and self-powered characteristic of this burner are attractive advantages over conventional residential burners. However, although a hydronic system using pulse combustion was commerically offered over two decades ago, there are no marketed systems in use today (Reference 5-7). AGAL is currently investigating pulse combustion for residential heating using a condensing exhaust gas system. Preliminary NO_x emissions from pulse combustion of Cleveland natural gas range between 19 and 20 ng/J (0.044 and 0.047 $lb/10^6$ Btu) (Reference 5-8). Commercialization of a pulse combustor residential heating system is expected in 1981 (Reference 5-8).

5.1.1.7 Catalytic Combustors

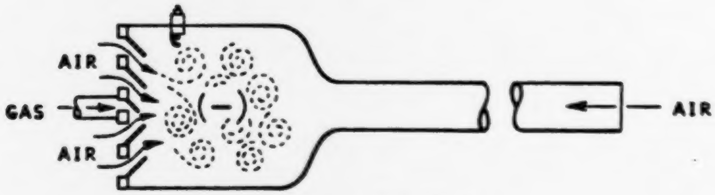
Catalytic residential combustors offer potential for very low-NO_x emissions while maintaining good combustion efficiency (Reference 5-7). The catalytic agent, usually in the precious metal family, promotes combustion of the fuel at low temperatures in the range of 755 to 1,366 K (900 to 2,000°F). At these low temperatures, thermal NO_x formation is significantly reduced. Large amounts of combustion air are, however,


SPARK PLUG
COMBUSTION CHAMBER
AIR
GAS
AIR
TAILPIPE
FLAPPER VALVES

A. STARTING OPERATION


(+)
EXHAUST PRODUCTS

B. EXHAUST PHASE (INLET CLOSED)


AIR
GAS
AIR
(−)
AIR

C. INTAKE PHASE (INLET OPEN)

Figure 5-5. Schematic operating cycle of a pulse combustion device.

required with catalytic combustors. The use of a condensing residential system, in which the latent heat of water vaporization is recovered by condensing the exhaust gas, is a viable option for minimizing heat losses due to high excess air levels. Catalytic combustors are not commercially available. However, research groups and trade organizations are now investigating its commercial feasibility for residential warm air and hot water systems burning natural gas. Performance and emission data for these systems have not yet been published.

5.1.2 Carbon Monoxide and Unburned Hydrocarbon Control

Gas-fired heating appliances and commercial boilers emit some level of CO and hydrocarbons during steady-state combustion. These levels are generally low for well adjusted (tuned) gas burners. AGA Laboratories reported an average CO emission level of about 8 ppm on an air-free basis for forced air furnaces and 4 to 70 ppm for hot water and steam boilers equipped with atmospheric gas burners. Aliphatic aldehydes expressed as formaldehyde (HCHO) generally averaged less than 1 ppm (Reference 5-1).

The well adjusted or tuned condition of residential furnaces and heaters equipped with atmospheric gas-fired burners can degrade with extended use in dirty environments. The low CO blue flame, characteristic of a tuned condition, will tend to eventually change with poor housekeeping or long time between service. The blue flame changes to a yellow-tip flame which is indicative of high CO emissions. AGAl indicated that yellow-tip gas flames, which occur during high input rates and low primary air aeration, can be the cause of CO emissions of 200 ppm and above (Reference 5-1).

The only practical control option available to reduce CO and other combustible emissions from untuned atmospheric gas burners is to provide a yearly service by skilled service personnel. During regularly scheduled service calls, the excess combustion air, which is the primary control variable, can be set at a correct operating range. Guidelines for minimizing air pollution and maintaining high efficiency for gas-fired furnaces, developed by Battelle and AGAL, were recently published by EPA (References 5-9 and 5-10). Figure 5-6 illustrates that the normal excess air level for well adjusted gas-fired heaters falls between 40 and 90 percent. Excess air settings much above 40 percent will unnecessarily reduce furnace efficiency due to more sensible heat being carried to the

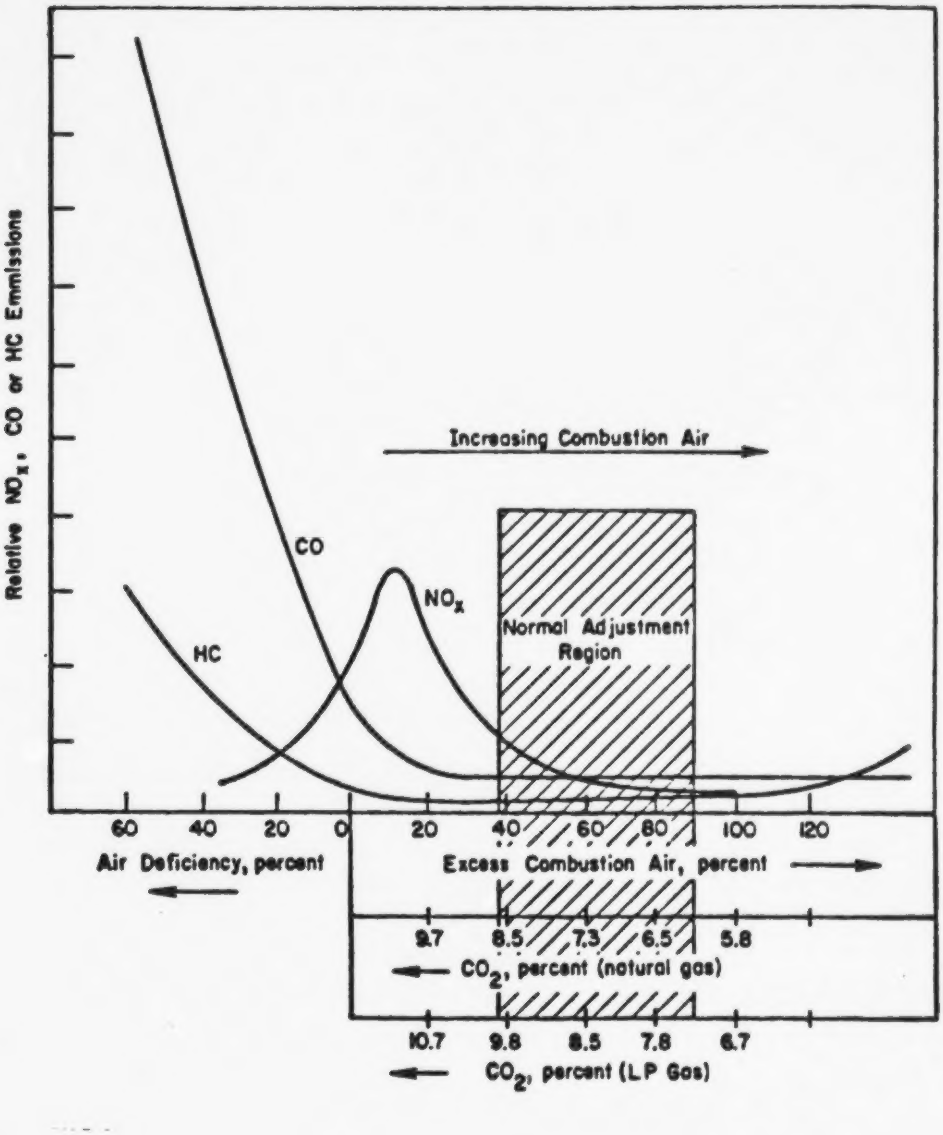


Figure 5-6. Effect of air adjustment on gaseous emissions for a typical atmospheric gas burner (Reference 5-9).

stack. Reduced furnace efficiency has an adverse effect on overall mass emissions because more fuel is burned and thus more pollutants are generated for a given amount of heat delivered . Maximum furnace efficiency for conventional equipment is limited to about 85 percent due to high stack gas temperatures necessary to avoid flue gas condensation. Typical factory adjusted residential furnaces have approximately 75 to 80 percent furnace efficiency at steady-state conditions.

As indicated in Section 4, CO and HC emissions occurring during furnace ignition and shutdown operation can account for most of these emissions. Therefore, one method of reducing CO and HC is to reduce the frequency of furnace cycling. This can be accomplished by reducing the firing rate of gas burners. Lower firing rates necessitate longer furnace-on periods in order to deliver a given amount of heat. Consequently, this reduces the number of on-off cycles over an entire heating season. Reduced firing rate (or "derating") also increases the residence time of combustion products in the firebox which tends to reduce steady- state combustible emissions. Reduced firing rate for existing furnaces can be accomplished by replacement of the existing burner orifice with smaller capacity orifices. Derating can accelerate furnace corrosion due to increased condensation during cyclic operation. This aspect can become a practical limitation to derating existing units. For new units, it is desirable to match closely the capacity of the furnace to the heat load requirements of the residence. Residential heating systems in the past have generally been oversized.

5.1.3 Cost and Energy Impact of Controls

Pending further verification of the performance of the Amana HTM, this burner design is presently considered the best available NO_x control technology for gas-fired residential and commercial heaters. The low-NO_x emission concept of the HTM design can be utilized for other furnace types according to Amana (Reference 5-4). An estimate for initial investment of about $1,000,000 has been reported by Amana for retooling to produce low-NO_x furnaces capable of meeting NO_x levels of 12 ng/J (0.028 lb/10^6 Btu). Annualized cost spread over 20 years to the consumer was reported at approximately $17 per furnace, or a cost effectiveness of $1.80 per kilogram ($0.80 per pound) of NO_x reduced (Reference 5-4). A more recent estimate for capital cost indicates that the HTM would cost approximately $100 more to the consumer than a conventional warm air and air conditioning unit of comparable size (Reference 5-11).

The incremental equipment cost for a new modulating warm air furnace has been reported in the range of $50 to $250 (References 5-4 and 5-7). Ranges in incremental costs of pulse combustion burner and catalytic burners have been estimated by Putnam, et al., at $300 to $600 and $150 to $250, respectively, for applications in flue gas condensing systems. The incremental cost of a radiant burner (surface combustion) was estimated to be $100 to 200 above that of a comparable noncondensing system (1979) (Reference 5-7). Because both the pulse and surface combustors and catalytic burner for domestic gas-fired heating are not commercially available, these cost estimates are considered preliminary.

A yearly service call to readjust residential furnaces for low smoke, CO and HC emissions and high efficiency was estimated at $33 to $55 (1976) for oil-fired units (References 5-12 and 5-13). This cost, which is based on estimated labor for nozzle cleaning or replacement, filter changes and excess air adjustment would be slightly less for gas-fired furnaces.

Since both the Amana and Bratko burner designs maintain good combustion efficiency at low excess air levels it is expected that NO_x reductions with these controls also contribute to a reduction in energy requirement for residential heating systems. While control of combustible emissions with burner servicing may increase energy requirements slightly through increases in excess air setting, the overall energy impact of CO and HC emission control for existing residential space heating equipment is considered minimal.

5.2 EMISSION CONTROL ALTERNATIVES FOR OIL-FIRED RESIDENTIAL SYSTEMS

Oil-fired residential and commercial heating systems emit NO_x, HC, and CO as well as particulates and smoke. Emission levels of these pollutants are generally higher than those from gas-fired units. Air pollutant control efforts for oil-fired residential equipment have been directed at controlling combustible emissions, smoke and particulate (soot) as well as NO_x through advanced burner and firebox design and improved maintenance procedures. NO_x controls which did not maintain low smoke and hydrocarbon emissions were generally not viewed by investigators as reasonable alternatives.

This section discusses control alternatives to reduce these pollutants for distillate oil-fired residential heating systems and commercial size boilers burning distillate or residual oil. Emphasis is placed on NO_x control technology for residential furnaces; however, control technology for other criteria pollutants and NO_x control techniques for commercial size hot water or steam boilers are also discussed.

5.2.1 Nitric Oxide Control

NO_x control technology development for residential oil-fired units was initially sponsored by the EPA and the American Petroleum Institute (API) (Reference 5-14). Control alternatives developed since these early studies include primarily new burner and firebox designs. The most promising control alternatives for residential heaters include:

- Flame retention burners
- Controlled mixing burner head
- Integral furnace design using controlled mixing burner head
- Blueray burner
- M.A.N. burner

With the exception of the controlled mixing head and integral furnace design, all other controls are commercially available or nearly so. The controlled mixing burner head and furnace are undergoing field tests to ascertain their performance, reliability and environmental impact. These controls are discussed in the following subsections.

NO_x control technology for commercial size hot water or steam boilers is less advanced than for residential systems. However, several control alternatives investigated for small industrial boilers during recent EPA sponsored field studies (References 5-15, 5-16 and 5-17) may be applicable to the commercial-size units of the same design. For example, the commercial size firetubes are very similar to the small packaged industrial size firetubes. NO_x control techniques that have been investigated for industrial firetube boilers include (References 5-15 through 5-18):

- Low excess air (LEA)
- Flue gas recirculation (FGR)

- Staged combustion air (SCA)
- Low-NO_x burners (LNB)

Although FGR and SCA are very effective in reducing NO_x, both techniques may be either technically impractical or too costly for application on small commercial units. These boilers are generally operated unattended with heat loads changing frequently. A low NO_x burner for application on packaged boilers with heat input capacity of less than 2.9 MW (10 x 10^6 Btu/hr) is currently under development (Reference 5-19). Another LNB, developed and currently being field tested by TRW Corporation, may be the most feasible alternative for significant NO_x reductions for these units. However, the TRW LNB development has been limited to burner capacity above 2.9 MW (10 x 10^6 Btu/hr). TRW representatives indicate that if a market for NO_x control for commercial steam and hot water boilers develops, TRW may then investigate the potential for scaling down the industrial size burner to a commercial unit with heat-input capacity as low as 0.15 MW (0.5 x 10^6 Btu/hr) (Reference 5-20). Additional information on combustion modification NO_x controls for small industrial package boilers with potential application to commercial size boilers is given in References 5-21 and 5-22.

5.2.1.1 Flame Retention Burners

The flame retention burner head has been commercially available for some time. Residential burners using flame retention devices accounted for over 10 percent of the oil-fired burner designs for space heating equipment in 1972 (Reference 5-23) and essentially all small burners currently installed with new furnaces and boilers are flame retention types. These devices in the form of plates, grids or cones produce a high swirling flow which holds the flame at the retention ring. Local recirculation zones reduce smoke emissions and allow for operation at low excess air levels.

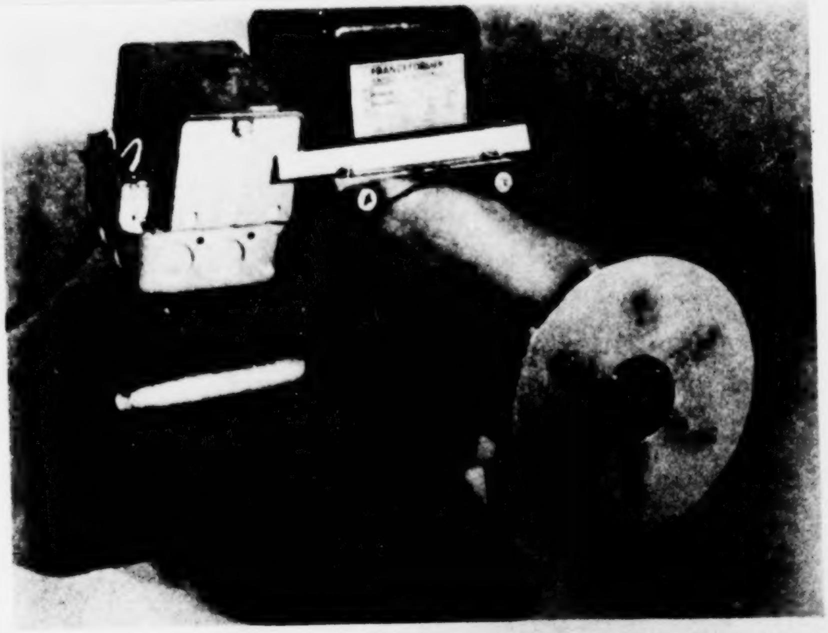
Laboratory experiments have shown that most flame retention burners increase NO_x emissions (References 5-12 and 5-23). In a study on the effect of burner type on emissions from a residential warm air furnace, Hall reported NO_x emissions from a conventional high pressure atomizing burner at 37 ng/J as NO_2 (0.09 lb/10^6 Btu). Ten commercially available flame retention burners were tested in the same furnace, producing NO_x emissions in the range 26 to 59 ng/J as NO_2 (0.06 to 0.14 lb/10^6 Btu) (Reference 5-12). Only the ABC Mite burner model illustrated in Figure 3-6 (see Section 3) was found to reduce NO_x by about 30 percent, from 37 to 26 ng/J, while also reducing smoke emissions from a Bacharach number of 2.9 to 2.0 (Reference 5-12). During a field investigation of residential systems, Barrett, _et al._, reported NO_x emissions from conventional burner systems, in "as-found" conditions, in the range of 47 to 85 ng/J as NO_2 (0.11 to 0.20 lb/10^6 Btu). NO_x emissions from domestic heating systems equipped with flame retention burners ranged between 48 and 88 ng/J as NO_2 (0.11 to 0.21 lb/10^6 Btu) (Reference 5-23).

In general, most flame retention devices are desirable for all conventional high pressure atomizing gun burners because they allow for operation at low excess air levels and stay tuned longer. These two characteristics improve furnace efficiency and reduce overall emissions through reduced fuel consumption.

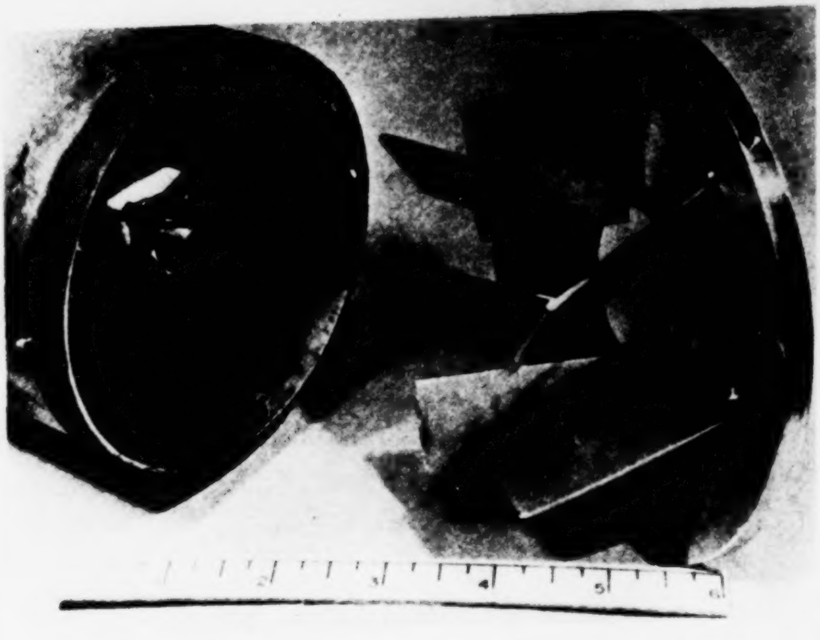
5.2.1.2 Controlled Mixing Burner Head

A controlled mixing burner head for retrofit application to residential oil heating equipment was developed by Rocketdyne Division of Rockwell International under EPA sponsorship (Reference 5-24). The principal characteristics of this burner head are: (1) no flame retention device, (2) choke diameter related quantitatively to the firing rate, and (3) oversize internal peripheral vanes oriented at 25 degrees relative to the blast tube axis (Reference 5-25). The choke diameter was attributed to reducing NO_x by promoting a uniform one-dimensional (plug) flow while the internal vanes maintained low carbonaceous pollutant emissions at low excess air operation. Figure 5-7 illustrates the details of this burner design.

Results of laboratory studies indicated that the controlled mixing burner head design is feasible for commercialization and could be retrofitted on existing residential space-heating equipment which presently use conventional high pressure atomized oil burners. Sheet metal stamping was found to be the best fabrication method for commercial production of the burner head. The burners were found to operate successfully with long life potential. NO_x reduction capability was



(a) External View **5DZ21-8/6/73-S1**



(b) Optimum 1 ml/s
Burner Head

5DZ21-8/6/73-S1A

Figure 5-7. 1 ml/s (gph) controlled mixing low-emission residential oil burner (Reference 5-25).

investigated by testing two commercially available warm air furnaces retrofitted with the EPA/Rocketdyne burner head. Results of the tests are illustrated in Figure 5-8. Based on these data, Combs and Okuda estimated that retrofit of this burner head design would reduce NO_x emissions by 20 percent with potential increases in season-averaged thermal efficiency as high as 5 percent (Reference 5-25).

5.2.1.3 Integral Furnace Design With Controlled Mixing Burner Head

Although appreciable NO_x reductions (20 percent) were achieved with the controlled mixing burner head, minimum NO_x emissions necessitated optimization of the entire furnace system. Under the same EPA furnace development program, Rocketdyne developed a cylindrical combustor to be used with the low-NO_x burner to produce a low emission integral furnace design. A NO_x emission level of 0.5 g/kg (1.0 lb/ton) or about 11 ng/J (0.03 lb/10^6 Btu) heat input was set as the emission goal for the program (Reference 5-25). The main features of the combustor design needed to achieve this level were identified as follows (Reference 5-26):

- Removal of approximately 20 percent of the heat input from the firebox based on the higher heating value of the oil
- An inside combustor diameter of 0.28 m (11 inches) or greater for a 1.05 ml of oil/s (1.0 gph)
- Long combustion chamber length for long residence time to prevent formation of combustible emissions at low excess air levels

The overall system utilizing the EPA/Rocketdyne combustor and burner head plus additional energy saving features, is illustrated in Figure 5-9. As shown, an air-cooled finned firebox was selected. The figure also highlights other important features. Most important are the controlled mixing (labelled optimum in the figure) burner head for low-NO_x emissions at low excess air and the standby draft control used to reduce energy losses during furnace "off" cycle. During laboratory tests the prototype furnace reduced NO_x emissions by 65 to 70 percent to about 0.63 g/kg (1.26 lb/ton) level, short of the original program goal. Steady-state and cyclical efficiencies averaged nearly 85 and 75 percent respectively (Reference 5-26).

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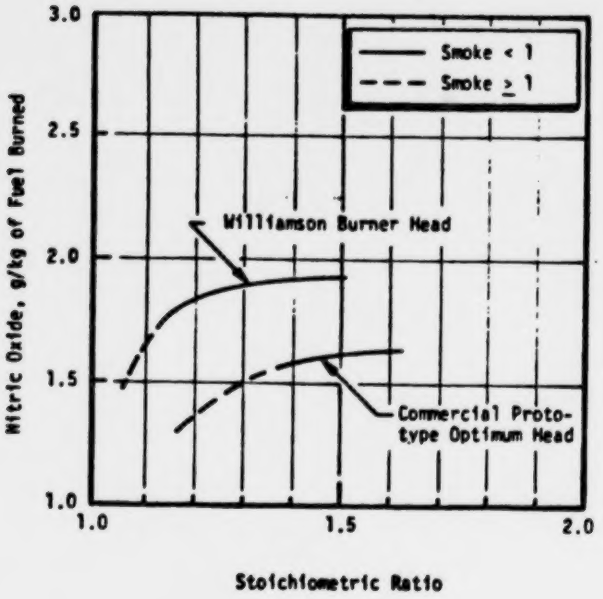
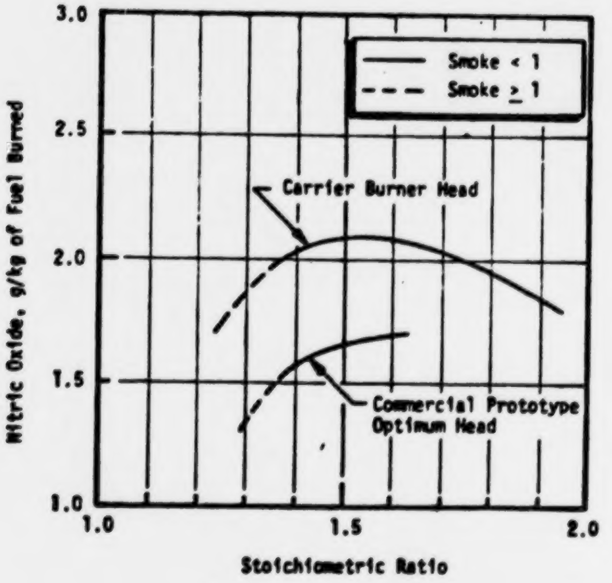


A. Williamson 1166-15 Furnace System



B. Carrier 58HV-156 Furnace System

Figure 5-8. Comparative NO emissions for the controlled mixing EPA/Rocketdyne burner head as a retrofit device in two warm-air furnaces (Reference 5-26).

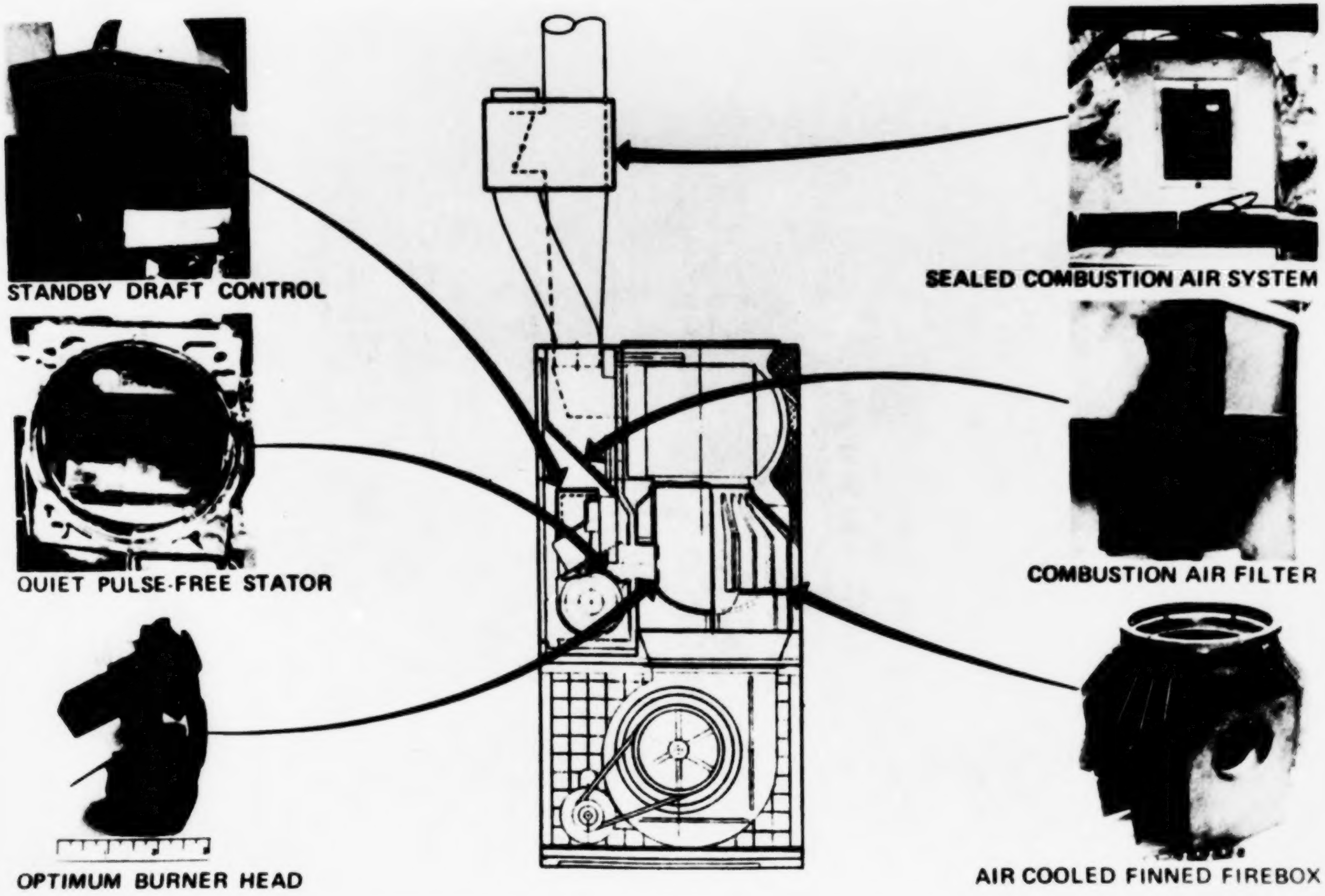

STANDBY DRAFT CONTROL
QUIET PULSE-FREE STATOR
OPTIMUM BURNER HEAD
SEALED COMBUSTION AIR SYSTEM
COMBUSTION AIR FILTER
AIR COOLED FINNED FIREBOX

Figure 5-9. EPA low-emission integrated furnace components (Reference 5-28).

Recently six units based on this prototype design were installed in eastern U.S. residences and operated during the 1977-78 heating season. During reported tests, NO_x emissions were measured at 0.65 g/kg (1.30 lb/ton) of fuel burned. This NO_x level corresponds to an average reduction of 65 percent from levels measured with conventional furnace designs. Steady-state and cyclical efficiencies averaged 84 and 74 percent respectively and, in general, did not degrade over the heating season (Reference 5-29). These high efficiencies translated to 18.5 percent fuel savings when compared to the two prior heating seasons. A second field test program is under way to assess the reliability of the system and supplement the existing data base.

5.2.1.4 Blueray Burner

In 1973, the Blueray System Incorporated, Jericho, New York, patented a low emission high efficiency oil-fired warm air furnace (U.S. Patent No. 3,741,166). The Blueray furnace uses a new burner design which produces a soft, even blue flame instead of the conventional orange-yellow flame. Figure 5-10 illustrates a schematic of the Blueray burner assembly. Combustion gases representing about 50 percent of the stoichiometric air requirement are recirculated to produce smoke-free, blue flame combustion at low excess air. Most luminous soot particles are eliminated during the reburning. Because the blue flame burner is matched to the combustion volume to obtain the desired recirculation pattern, the Blueray system is available only as a burner-furnace package. Retrofit to existing furnaces is not practical. The "blue flame" burner is sold in warm air furnaces in two firing ranges, 0.63 to 0.79 ml/s (0.60 to 0.75 gph).

Nitric oxide emissions from a 0.79 ml/s (0.75 gph) furnace were measured at between 25 and 35 ppm or about 0.41 g/kg (0.82 lb/ton) of fuel oil burned. CO emissions from the same furnace were 15 to 25 ppm and UHC 3 to 5 ppm, while smoke emissions were nearly zero (Reference 5-30). In addition to the low-NO_x operation, the Blueray furnace operates at high steady-state efficiency averaging 83 to 84.5 percent. The furnace compactness and low operating noise are also desirable features.

In 1974, Underwriters Laboratory (UL) certified the 0.63 and 0.79 ml/s (0.6 to 0.75 gph) furnace as meeting the UL and ANSI standards. Since then over one thousand furnaces have been installed in many eastern

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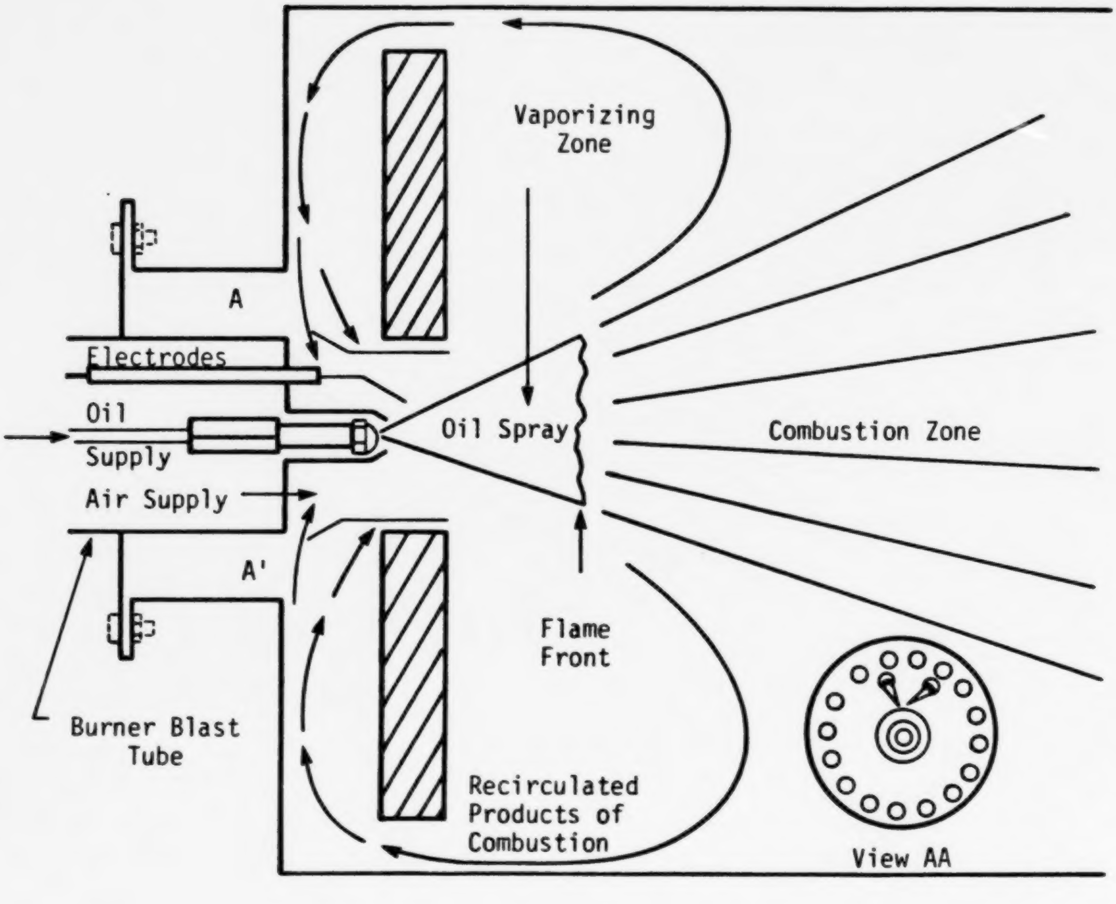
Vaporizing Zone
A
Electrodes
Oil Supply
Oil Spray
Combustion Zone
Air Supply
A'
Flame Front
Burner Blast Tube
Recirculated Products of Combustion
View AA

Figure 5-10. Schematic illustration of the Blueray head assembly (Reference 5-30).

states. Recently, under the current NO_x Control Environmental Assessment (NO_x EA) program, one such furnace was field tested (Reference 5-31). Nitric oxides, CO and UHC emissions were measured during continuous and cyclical operation. Cycles consisted of 10 minutes on and 10 minutes off periods. Pollutant emissions in ppm measured with 20 percent excess air are listed below:

	Cyclical Operation	Continuous Operation
NO, average	11	16
NO, peak	16	16
CO, average	160	25
CO, peak	2,000	25
UHC, average	23	0
UHC, peak	390	0

Cyclic NO emissions (11 ppm uncorrected) correspond to about 0.35 g/kg (0.70 lb/ton) of fuel burned and are lower than those reported in Reference 5-30. Section 6 presents trace elements and organic emission data also obtained during the NO_x EA test program on the Blueray furnace. These data are then compared with recently published test data obtained by TRW for conventional distillate oil-fired residential furnaces.

5.2.1.5 M.A.N. Burner

The M.A.N. burner was developed and licensed by the German Research and Testing Laboratory for Air and Space Travel. Figure 5-11 illustrates a schematic of the burner. Hot combustion gases are recirculated to achieve complete combustion in a manner similar to the Blueray system. The main difference between the two burners is that the Blueray burner uses an "external" gas recirculation system which requires an air tight combustion chamber to prevent air leaks. The M.A.N. burner, however, recirculates the hot combustion gases internally within the blast tube. This design feature may permit retrofit installation of the burner on existing warm air furnaces.

The M.A.N. burner, which is commercially available in Europe in firing capacities ranging from 0.53 to 0.80 ml/s (0.5 to 0.75 gph) is being tested at the EPA Industrial Environmental Research Laboratory

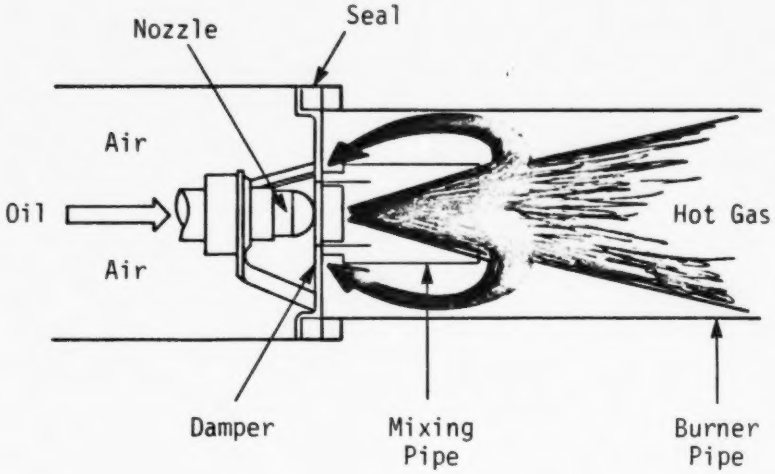

Figure 5-11. Schematic of the M.A.N. residential oil-fired rocketburner (Reference 5-32).

(IERL) (Reference 5-33). Manufacturer estimates of NO_x emissions range from less than 20 to 50 ppm. Lowest NO_x emissions are obtained with an air-cooled blast tube. Reported CO emissions are less than 100 ppm and smoke Bacharch number less than 1.0 (Reference 5-33).

5.2.2 Carbon Monoxide and Unburned Hydrocarbon Control

Emissions of CO and UHC from residential space heating equipment are primarily a function of fuel consumption, cycle frequency, and excess air levels. In general, CO and UHC emission reduction can be accomplished by: (1) reducing fuel consumption with increased overall system efficiency or reduced heat demand, (2) reducing the number of on-off cycles which cause combustible emission peaks, and (3) assuring proper normal excess air setting with tuning and scheduled burner maintenance. The following subsections describe the implementation of these control approaches and review published performance data.

5.2.2.1 Reduction in Fuel Consumption

Increased steady-state and cyclical thermal efficiency for residential oil-fired heaters can best be achieved with integrated burner and combustor system design. Advanced concepts such as the flame retention burner and the Blueray or EPA/Rocketdyne furnace design increase steady-state efficiency primarily by achieving complete combustion at low excess air. This increases efficiency by 5 to 10 percentage points compared to conventional furnaces (Reference 5-26). Overall seasonal emissions are reduced proportionally to the fuel saving.

Reduction in fuel consumption can also be accomplished by installing energy saving devices such as chimney or duct dampers. These devices increase cyclical furnace efficiency by reducing heat loss during the standby portion of the heating cycle. Standby heat losses are caused by cooling of the combustor by natural draft air circulation. During a field study performed in Canada, chimney dampers reduced seasonal CO emissions from two warm air furnaces by 2.4 and 19 percent, respectively (Reference 5-34). The difference in performance between the two sources was caused by variation in cycling frequency.

A third and most straightforward method of reducing fuel consumption and thus CO and UHC emissions, is to turn down the thermostat or increase thermostat anticipator settings. Overnight thermostat cutback by 3 to 5 K (5 to 9^{0}F) reduced seasonal CO emissions by 9 to 27 percent (Reference 5-34). The relative performance of reduction in fuel consumption on seasonal CO and UHC emissions depends highly on the number of cycles the residential furnace or boiler undergoes. Furnaces with a high cycle frequency have much higher combustible emissions than those furnaces which are cycled less frequently. Thus, reduction in fuel consumption is less effective in reducing seasonal CO emissions from furnaces which cycle frequently during the entire heating season (Reference 5-34).

5.2.2.2 Reduced Cycle Frequency

Reduced firing rate capacity and changes in thermostat anticipator setting are the principal methods to reduce the cycling frequency of residential heating systems. Reduced firing rate causes the furnace to operate for longer periods to meet load requirements. Changes in thermostat anticipator setting can result in a wider temperature "window" in which the furnace is on and thus reduces furnace cycle frequency. To achieve this increase in temperature window, the anticipator setting is either increased or decreased depending on the thermostat wiring arrangement. Both methods of reduced firing rate and change in anticipator setting independently reduce the number of times the burner is ignited and shut off, thus reducing overall CO and UHC emissions over an entire heating season. Furthermore, overall furnace heating fuel efficiency to the home is increased.

Existing oil-fired residential heating systems are generally oversized with respect to the residential load demand. A recent study of 26 residential systems (six forced warm air, 16 hot water, and four steam or heat transfer fluid) in the Boston area by Bonne et al., revealed that the excess capacity of these residential oil burners averaged 147 percent (i.e., 247 percent of design capacity) (Reference 5-35). Twelve oil-fired burners had a minimum capacity in the range of 1.05 to 1.42 ml/s (1 to 1.35 gph) and 14 others had a capacity of greater than 1.42 ml/s (1.35 gph) (Reference 5-36). When a reduction in firing rate of these units was attempted by reducing the size of oil nozzles 28 percent, however, an increase in excess air of about 37 percent was found necessary to prevent excess smoke emissions. Soot formation was promoted by reduced atomization efficiency with the smaller nozzles. Also smaller burners tend to become plugged after short operating periods. Overall, Bonne, et al., concluded that, even when accounting for the negative aspects of retrofitting smaller capacity wastes on existing oversized units (such as increased excess air, increased electrical energy consumption by the blower motor, oil pump and system recirculating fan/pump due to longer on-times, and higher furnace infiltration losses due to increased air flow through the stack draft diverter), the net result was a modest decrease in seasonal fuel consumption and cost for space heating by 5.2 and 3.7 percent, respectively (Reference 5-36).

Janssen, et al., investigated the feasibility of a thermal aerosol generator as a residential oil burner which could operate efficiently at firing rates reduced to as low as 0.42 ml/s (0.4 gph) while using an excess capacity nozzle in the range of 0.89 to 1.31 ml/s (0.85 to 1.25 gph). Reducing the oil flow instead of using smaller 0.42 ml/s (0.4 gph) capacity pressure atomizing nozzle eliminates the potential plugging problem of very small capacity nozzles (Reference 5-37). In the thermal aerosol burner the distillate oil was heated to over 373 K (212^{o}F). The use of heated oil improves atomization (i.e., smaller oil drops and thus better fuel air mixing). at low pressure and reduced firing rate. The thermal aerosol oil burner achieved good atomization with low CO and UHC emissions at 0.42 ml/s (0.4 gph) oil flowrate (representing a 53 to 68 percent nozzle capacity reduction) and low excess air. Heating the fuel was also found to lower emissions during start-up. Fuel oil heated to 423 K (302°F) produced zero smoke in less than 1.5 minutes after ignition (Reference 5-37). During most tests, NO_x emissions also decreased with increasing fuel oil temperature and pressure.

In another study, Hayden et al., reduced the firing rate on one furnace, thus reducing seasonal number of cycles from 3,400 the previous season to 3,301 during the test season. Seasonal CO emissions were reduced 14.2 percent (Reference 5-34) with approximately 9 percent of this reduction attributable to fuel savings. Reducing the cycling frequency also generally significantly improves the overall furnace efficiency. "Off" cycle heat losses due to the buoyancy induced drafts in the stack and combustion system are reduced due to the fewer numbers of standby periods. When Katzman and Monat reduced the firing rate of 18 oil-fired residential heating systems by 36 percent, the resulting average increase in seasonal efficiency was 14 percent (Reference 5-38). Overall seasonal mass emissions are generally reduced through a reduction in fuel consumption.

Increased thermostat anticipator setting showed a dramatic effect on cycling frequency and seasonal CO emissions during tests on oil-fired residential heaters (Reference 5-34). Two hot water hydronic systems with unusually high cyclic frequency (approximately 11 to 22 thousand cycles per season) were tested with an increased anticipator setting of the Honeywell thermostats. The total number of cycles decreased an average of 55 percent. CO was reduced over 40 percent when compared to total seasonal emissions of the previous heating season. These dramatic CO emission reductions are indicative of the importance of combustible emissions during cyclic operation.

5.2.2.3 Burner Tuning and Maintenance

Several investigators have shown that CO and UHC emissions can be reduced significantly by adjusting or tuning existing burners, and by replacing worn-out burner components or entire furnaces. One team of investigators studied the emissions from 33 residential oil-fired units during the 1970 to 1972 heating season (Reference 5-23). Pollutant emissions were measured in the "as found" condition and after tuning. The procedure for tuning included:

- Cleaning and adjusting the ignition electrodes
- Cleaning the blast tube and blower shell
- Cleaning or replacing the nozzles
- Cleaning or replacing the oil filter
- Sealing air leaks at the inspection door, around the blast tube or at other easily accessible locations
- Changing the draft regulation setting

Three of the 33 units tested were found to be in such poor condition that they had to be replaced.

Table 5-3 summarizes the reductions in mean pollutant emissions that could be accomplished by identifying and replacing the units obviously in poor condition and by tuning the remaining units. Combustible emissions were reduced substantially only by replacing the three furnaces found in poor condition. Actual tuning added only 3 percent reduction for UHC and 16 percent for CO. Barrett, et al., also showed that overall thermal efficiency for the units tested increased 1.7 percent on the average (Reference 5-23).

TABLE 5-3. EFFECT ON MEAN EMISSION OF IDENTIFYING AND REPLACING RESIDENTIAL UNITS IN POOR CONDITION AND TUNING (Reference 5-23)

	Reduction in Emissions, percent		
	Step 1	Step 2	
Pollutant	Replacements of Worn-Out Units	Replacement of Worn-out Units and Tuning of Remaining Units	Improvement Due Only to Tuning
Smoke	--	59	59
CO	65	81	16
HC	87	90	3
NO_x	No Change	No Change	0
Filterable Particulate	17	24	7

As indicated in Table 5-3, tuning has essentially no effect on NO emissions except for the indirect reduction due to increased thermal efficiency and hence reduced fuel consumption. Tuning was found to be most effective for smoke emissions. The overall dramatic reduction in emissions accomplished simply by replacing 9 percent of the units tested indicates that unnecessary combustible pollutants are emitted from old furnaces with worn-out or damaged burners. Hall, et al., and Barrett, et al., estimated that 9 to 30 percent of existing oil-fired residential burners are worn out and in need of replacement (References 5-12 and 5-23). Lifetime of an oil-fired residential furnace averages 15 years (Reference 5-13).

In addition to reducing CO and UHC emissions through burner tune up, an annual maintenance program is suggested for low emissions and maximum thermal efficiency throughout each heating season (Reference 5-12). Performance of residential oil-fired heaters and, to some extent, commercial boilers deteriorates with time. The decrease in performance if unchecked, can lead to very poor operation. As much as 10 percent efficiency drop has been measured over a period of 10 weeks on one experimental furnace (Reference 5-12). One reason is that some of the soot which is formed during inefficient operation adheres to the heat transfer surface. Soot accumulation will eventually lead to reduction in heat transfer, higher stack temperatures, and increased emissions due to increased fuel usage.

EPA Guidelines for tuning and maintenance of oil-fired residential and commercial heating systems recommend the following (References 5-39 and 5-40):

- Inspect fuel oil nozzle; clean or replace if necessary
- Replace or install in-line oil filter
- Clean heat transfer surfaces of soot or other deposits
- Seal air leaks
- Set fuel oil pressure to manufacturer's recommendations
- Set fuel oil temperature to provide manufacturer's recommended viscosity (only for large commercial units burning other than distillate oils)
- Assure timely shut-off of fuel flow and proper ignition without excessive emissions
- Set excess air to recommended CO_2 levels without incurring excessive CO or smoke emissions

These maintenance procedures performed by skilled service personnel will ensure that residential and commercial oil-fired heaters and boilers do not cause unnecessary combustible emissions and that high thermal efficiency of the unit is maintained.

5.2.3 Smoke and Particulate Control

Essentially all oil-fired residential heating units are fired with No. 2 distillate oil. Particulate emissions from the burning of this grade of oil are usually small compared with those from units fired with residual oil. High smoke or particulate readings with distillate are mostly due to improper air-to-fuel ratios, improper draft, worn-out burner components, or poor burner and combustion chamber design.

As with CO and UHC control, an effective and practical technique to reduce particulate and smoke emissions from residential oil burners is to keep them well maintained. Significant improvements can also be obtained through the use of new, well designed burners and combustion chambers. Also, energy saving devices which improve steady-state efficiency and reduce cyclic frequency reduce seasonal particulate and smoke emissions indirectly through reduced fuel consumption.

In general, those controls discussed in the previous section for CO and UHC emissions are also effective in reducing smoke and particulates from residential heaters. In addition, delayed action solenoid oil valves have been tested successfully to reduce smoke emissions during start-up and shut-down periods when carbonaceous emissions are highest. This control is discussed in Section 5.2.3.4.

5.2.3.1 Burner Tuning and Maintenance

In Battelle's tests of residential and commercial heating units (Reference 5-23), tuning of the serviceable units reduced the mean values of the Bacharach Number considerably. Results of these tests for smoke emissions are summarized in Figure 5-12. The mean Bacharach Number was 3.2 for the "as found" condition. After tuning, the mean smoke number was reduced 59 percent to 1.3 (see Table 5-3). Moreover, after tuning, all of the serviceable units could have complied with a standard of Bacharach No. 3 and nearly 90 percent could have even complied with a level of 2. Reduction in emissions of filterable particulate attributed to tuning averaged 7 percent. The guidelines for tuning and maintenance discussed in the previous section are also valid for control of smoke and particulate emissions.

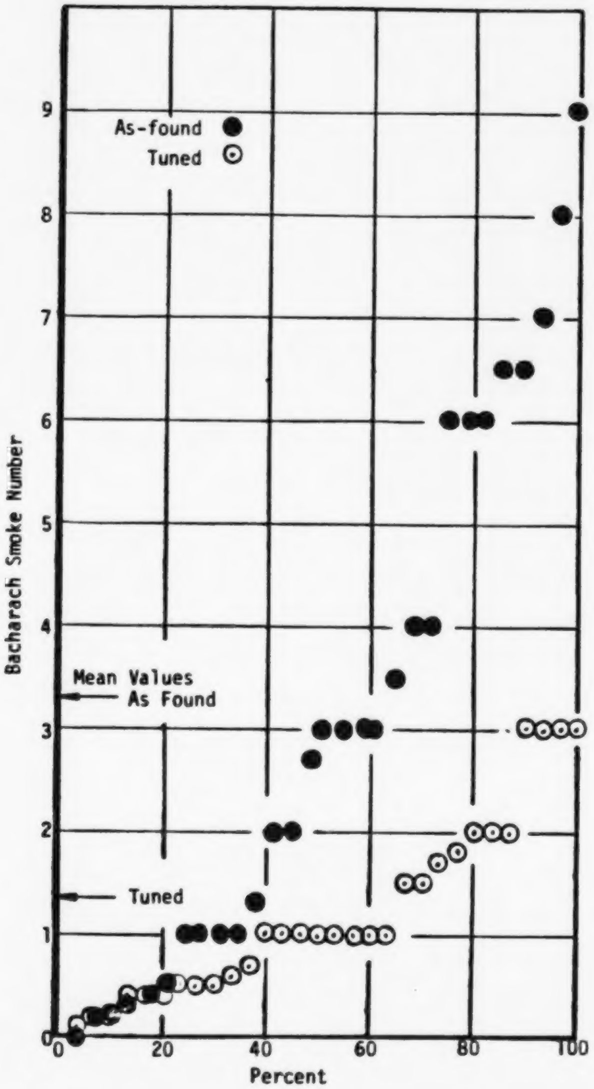

Figure 5-12. Distribution of smoke emission for residential units (Reference 5-23).

5.2.3.2 Burners and Combustion Chamber Redesign

Advanced low-NO_x burners for residential oil-fired heaters are also capable of operating at low excess air with essentially smoke-free flue gas. These burner designs rely on optimal choices for swirl over velocity to obtain the desired turbulence level and residence time (EPA/Rocketdyne controlled mixing burner). In addition, many use either internal or external flue gas recirculation for complete burnout (Blueray and M.A.N. burners). Flame retention devices which produce a more stable, compact and intense flame have also been demonstrated to reduce smoke and particulate emissions. In one study, one type of flame retention burner emitted less smoke than the conventional unit (average Bacharach Number of 1.2 for the retention head versus 2.9 for the others) (Reference 5-12). A set of field test results also showed that smoke and particulate were lower for retention head burners than for conventional designs. Smoke emissions were reduced 26 percent and filterable particulate emissions were reduced 50 percent on the average (Reference 5-23).

5.2.3.3 Reduced Fuel Consumption and Reduced Cycle Frequency

As indicated in the discussion for CO and UHC control, reduced fuel consumption can be accomplished by a variety of methods. Installation of chimney or duct dampers reduced fuel consumption by 3 to 9 percent on two warm-air furnaces, decreasing seasonal particulate emissions from 2.2 to 17.2 percent. Overnight reductions in thermostat settings of 3 to 5 K (5 to 9^{o}F) reduces seasonal fuel consumption by 7 to 15 percent and decreased particulate emissions by about 12 to 24 percent (Reference 5-34). Increased thermostat anticipator (resulting in longer on-times reduced fuel consumption marginally, but the particulate emission reductions were significant -- 32 to 33 percent -- primarily caused by a reduction in cyclic frequency of warm-air furnaces tested (Reference 5-34). Reduced firing rate resulted in seasonal particulate emission reductions of only about 4 percent. These were caused by a 9 percent reduction in fuel oil consumed and a 3 percent reduction in cycling frequency (Reference 5-34).

5.2.3.4 Delayed Action Solenoid Valve

Katzman and Weitzman found that the installation of delayed action solenoid valves reduced the average smoke number from 6.3 to 2.3 during furnace startup and 8.3 to 0.7 during shutdown periods (Reference 5-13).

During start up, the solenoid delayed the opening of the oil valve until the burner air blower had reached full speed. This prevented the poor startup performance caused by insufficient combustion air and mixing. During shut down, the delayed oil valve closed off immediately providing a clean flame cut off. Without the valve, the speed of the blower generally decreased to approximately 900 rpm (25 percent of capacity) before the oil flow was actually shut off. Smoke emissions during start up and shut off periods without the delayed oil valve ranged from Bacharach numbers of 5 to 9 (Reference 5-13).

5.2.4 Cost and Energy Impact of Controls

Reported control costs for oil-fired residential heating systems vary significantly according to the type of control and application. For example, the 1976 retrofit costs of NO_x controls ranged from about $38 for the burner head developed by Rocketdyne to about $339 for a reduced capacity high-efficiency flame retention burner. More recent differential costs of a new low-NO_x furnace, such as the Blueray or the Rocketdyne unit, range from about $100 to $250 over the cost of a conventional furnace.

Although inflation has increased the cost of these controls over the past few years since 1976, the cost of fuel oil has also risen even more dramatically than the average rate of inflation has. Therefore, the energy saving associated with most retrofit controls and new low-emission high-efficiency furnaces is such that the initial investment is often recovered within the first two heating seasons.

The volume production cost of the burner head by Rocketdyne was estimated to be only $1.50 (Reference 5-25). Including the installation cost, the total investment in 1976 was estimated at about $38 per burner. Since the burner head increases seasonal efficiency by about 5 percent on the average, the payback period should be rather short (i.e., generally less than a year).

As discussed in Section 5.2.1.1, retrofit of flame retention cone heads on existing high pressure gun atomizing oil burners was determined to be feasible. The cost and energy savings of retrofit installation of one flame retention head with a new nozzle rated at lower firing capacity was also estimated. The average 1976 investment cost was estimated to be $45 on the average and the energy savings would amount to approximately $110 for a payback period of less than 1 year (Reference 5-13).

The cost to retrofit a new flame retention burner with a reduced firing capacity was estimated to require an initial investment of $339 in 1976 (Reference 5-13). Accounting for inflation, this cost would increase to about $385 in 1978. However, the annual fuel oil saving was estimated to average 2009 liters (531 gallons) when compared to fuel oil consumptions of existing low-efficiency furnaces (Reference 5-13). Considering that the cost of home heating oil in 1978 was approximately $0.20/l ($0.80/gal) annual savings would amount to about $400. Therefore, the payback period for the reduced capacity flame retention burner would be approximately 1 year.

Rocketdyne, along with EPA, has applied for a patent for the new furnace system discussed in Section 5.3.1.2. The incremental equipment cost of this furnace compared with a conventional warm-air heater was recently estimated to be about $250 (Reference 5-41). Assuming an annual heating oil bill of $1,000 per household and considering the reported savings in fuel consumption of about 18 percent, the payback period for this initial investment is less than 2 years.

The Blueray furnace, equipped with the "blue flame" low-NO_x recirculating burner is commercially available with over one-thousand units already in place. The cost of the Blueray furnace was estimated to be about $100 more than the cost of a conventional warm air heating system (Reference 5-42). This differential investment would generally be recovered in less than a year.

No cost information is available for the M.A.N. burner. Foreign manufacturers are planning to introduce this burner design in the U.S. Recently the burner has undergone tests at EPA laboratories. Commercial availability is expected in 1980 (Reference 5-43).

Tuning of a residential oil-fired furnace for low emissions and high thermal efficiency was estimated to cost $33 to $55 (1976) based on the labor cost estimates by Katzman and Weitzman for installation of flame retention cones and nozzles and adjustment of combustion air flow (Reference 5-13). Since unit efficiency generally increases with tuning, this initial cost is offset by savings in fuel consumption. Manufacturers and service organizations recommend that residential heaters be serviced once a year, preferably at the beginning of the heating season (Reference 5-12).

Various other control techniques primarily aimed at reducing oil consumption for residential heating and improving seasonal thermal efficiency can be easily implemented by the homeowner. Change of thermostat anticipator setting if adjusted by the homeowner and manual overnight thermostat cut-back require no cost and reduce energy consumption plus reduce overall emissions. Installation of positive stack dampers requires some initial investment cost. The recently reported cost of installed automatic chimney dampers is $200 -- $120 for the damper (Reference 5-44). Thus, it can be estimated that the payback period for this energy saving device could also be relatively short.

In general, all air pollutant control techniques improve unit thermal efficiency as well as reduce seasonal NO_x and combustible emissions. For this reason, the initial investment required for new burners, furnaces or scheduled tuning can in many cases be compensated with reductions in fuel oil consumption which translate to savings for the homeowner.

5.3 EMISSION CONTROL ALTERNATIVES FOR SOLID FUEL-FIRED RESIDENTIAL SYSTEMS

Solid fuel-fired residential and commercial systems include hand-fired and stoker-fired systems plus some wood-fired stoves, furnaces, and boilers. Residential stokers are hopper fed or bin fed if equipped with a mechanical underfeed system. Larger commercial stokers can be of the overfeed, underfeed and spreader type. However, underfeed types are most common. Wood-fired residential furnaces are essentially all hand-fired.

NO_x emission control techniques for residential coal- and wood-fired heaters and boilers have not been widely investigated, primarily because of the declining use of this equipment type in the past. Also, small coal-fired equipment is not amenable to extensive modifications to control NO_x emissions. Excess air and overfire air injection in some units are the only feasible control alternatives which have some impact on the overall NO_x emissions. Wood heating has experienced a recent revival, and is the subject of a separate NO_x EA review to be published at a later date.

Excess air reduction in residential coal-fired equipment is very limited due to increases in carbonaceous emissions. Overfire air injection, only available with larger commercial size stokers, is only moderately effective in reducing NO_x. Overfire air which is generally used to control smoke and HC emissions from volatile coal combustion was found to be effective in achieving smokeless operation with some coals containing 20 percent or more volatile matter (Reference 5-45).

The emphasis of emission control from residential coal-fired equipment has been placed on reducing smoke and other carbonaceous pollutants. As discussed in Section 4, the combustion of high volatile bituminous coals in small residential systems produces high smoke and particulate emissions. A bituminous coal-fired furnace originally developed in the 1940's was investigated in a program to identify clean burning solid fuel-fired furnaces for residences. This furnace developed for Bituminous Coal Research, (BCR) Inc. uses a cross-feed principle of burning in which both the coal and combustion air move downward to the "hearth" or cross-fed portion of the fuel bed. Figure 5-13 illustrates a new coal-fired furnace/boiler based on the BCR design. This furnace can operate with 60 to 65 thermal efficiency and low smoke emission. This concept is applicable to boilers and space heating stoves as well as furnaces and can also burn wood or saw dust (Reference 5-47).

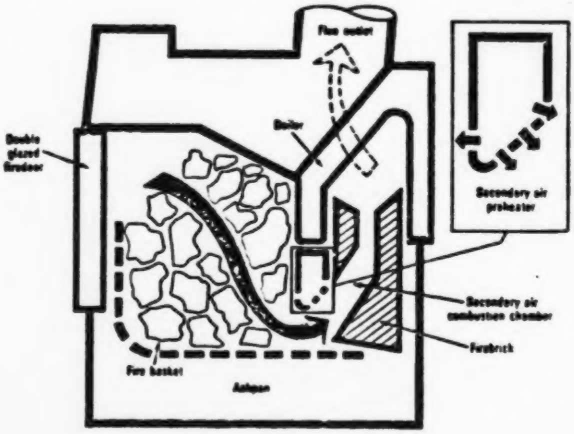

Figure 5-13. Schematic of the cross-feed combustion design for coal-fired residential furnaces (Reference 5-46).

Control techniques for wood-fired residential heaters have not been developed to any great extent. Since long term gas and oil supplies will continue to dwindle, wood represents a possible alternative to coal burning in home furnaces and residential and commercial boilers. Recently, however, the EPA has sponsored two test programs to quantify emissions and identify potential control options for wood burning appliances (Reference 5-48). In the first test program Monsanto tested two air tight stoves (one baffled and the other unbaffled) plus one fireplace for criteria pollutant, trace element and organics. In the second program, which is just underway, Battelle is to identify equipment and operating parameters which affect emissions. In addition, the program will assess which of these parameters can be safely varied to reduce emissions.

5.4 SUMMARY OF MOST EFFECTIVE CONTROL ALTERNATIVES FOR RESIDENTIAL SYSTEMS

In general, little of the NO_x control technology discussed earlier for gas- and oil-fired residential and commercial systems has been implemented in the field. Most emission control work for residential heaters has centered around tuning and maintenance of existing equipment or installation of new more efficient equipment for reduced fuel consumption and minimum visible emissions. Tuning usually reduces CO, HC, and particulates (smoke), however, without much effect on NO_x emissions. New furnace concepts utilize advanced burner designs which allow for efficient operation at low excess air. Some of these burners are also capable of low-NO_x emissions.

The following discussion summarizes the performance and cost of control techniques specifically aimed at reducing NO_x emissions from residential heaters. Based on performance, commercial availability, and cost, the best available NO_x control techniques are identified. Performance and cost of combustible emission controls for residential heaters are also summarized.

5.4.1 Gas-Fired Systems

Table 5-4 summarizes the performance of NO_x control equipment for natural gas-fired residential heaters. Baseline uncontrolled emission factors for the three major pollutants emitted from these sources are also presented. Additionally, steady-state and cycle efficiencies of baseline or "as found" residential units and controlled residential units are also

TABLE 5-4. PERFORMANCE SUMMARY OF LOW-NO_x CONTROL EQUIPMENT FOR NATURAL GAS-FIRED RESIDENTIAL HEATERS

Control	Average Operating Excess Air (percent)	Cyclic Pollutant Emissions ng/J heat input			Steady State Efficiency (percent)	Cycle Efficiency (percent)	1978 Installed Control Cost	Comments
		NO_x	CO	UHC[b]				
Conventional Units	40-120	28-45	8.6-25	3.3-33	70	60-65	c	Emission factors from References 5-49 and 5-50. Costs include installation.
Radiant Screens	40-120	15-18	6.4	NA	75	70	NA	Emissions of CO and HC can increase significantly if screen is not placed properly or deforms.
Secondary Air Baffles	60-80	22	14	NA	NA	NA	NA	Requires careful installation. Best suited for single port upshot burners.
Surface Combustion Burner	10	7.5	5.5-9.6	NA	NA	NA	$100-$200	Not commercially available. Still under development.
Amana (HTM)	NA	7.7	26	NA	85	80	$100-$300 over conventional furnace	Commercially available design. Spark ignited thus requires no pilot.
Modulating Furnace	NA	25	NA	NA	75	70	$50-$250 over conventional furnace	Furnace is essentially derated. Thus it requires longer operation to deliver a given heat load. furnace
Pulse Combustor	NA	19-20	NA	NA	95	95	$300-$600	Currently being investigated by AGAL. Efficiencies correspond to flue gas condensing systems.
Catalytic Combustor	NA	<5	NA	NA	90	85	$150-$250	Still at the R&D stage. Efficiencies correspond to flue gas condensing systems.

[a] Sum of NO + NO_2 reported as NO_2
[b] Unburned hydrocarbons calculated as methane (CH_4)
[c] Typical costs of uncontrolled unit $500-$800
[d] NA = not available.

presented to highlight the general improvement in thermal performance with any of the NO_x controls investigated.

The Amana HTM and Bratko burner designs represent the most effective control alternatives for gas-fired residential units. Reported NO_x reductions are generally greater than 80 percent accompanied by increases in thermal efficiencies of about 10 to 15 percent. However, recent tests with the Amana HTM combustor have not resulted in NO_x reduction efficiencies of 80 percent as previously reported by AGA. New tests have been scheduled (Reference 5-5).

The Amana furnace is the only commercially available unit. It is generally used for combined heating and air conditioning of residences and small commercial buildings. The cost to the consumer of an Amana heater is 20 to 40 percent more than the cost for a comparable unit. No known plans are under way to commercialize the Bratko burner.

Pulse combustion in a residential system has been reported to emit 19 to 20 ng NO_2/J (0.044 to 0.047 lb/10^6 Btu) (Reference 5-8). The incremental cost of a pulse combustion burner was estimated in the range of $300 to $600 for a condensing system with a seasonal efficiency of 95 percent (Reference 5-7). A catalytic burner also with a condensing system and a seasonal efficiency of 85 percent was estimated to range between $100 and $250 over the cost of conventional equipment (Reference 5-7). Both pulse and catalytic combustion for domestic heating are, however, not commercially available.

5.4.2 Oil-Fired Systems

Table 5-5 summarizes performance and cost of control equipment for residential distillate oil-fired heating equipment. These controls were primarily designed for warm air furnaces, however, the new burner/firebox technology of these systems may be applicable to residential hot water heaters or hydronic boilers.

The range in baseline NO_x emissions reflect data reported by Barrett, et al., (Reference 5-23) and Hall (Reference 5-12) for nonflame retention type burners. Barrett, et al., suggested an average NO_x emission factor of 55 ng/J as NO_2 (0.13 lb/10^6 Btu) for hot water and warm air systems utilizing both conventional and flame retention burners (Reference 5-23). This emission factor compares to 61 ng/J as NO_2 (0.14 lb/10^6 Btu) estimated by the EPA (Reference 5-50).

TABLE 5-5. PERFORMANCE SUMMARY OF LOW-NO_x CONTROL EQUIPMENT FOR DISTILLATE OIL-FIRED RESIDENTIAL HEATERS

Control	Average Operating Excess air (percent)	Cyclic Pollutant Emissions ng/J heat input					Steady State Efficiency (percent)	Cycle Efficiency (percent)	1978 Installed Control Cost	Comments
		NO_x[a]	CO	UHC[b]	Smoke Number	Particulate				
Conventional Units	50-85	37-85	15-30	3.0-9.0	3.2	7.6-30	75	65-70	c	Range in NO_x emissions is for residential systems not equipped with flame retention burners References 5-12 and 5-23). Emissions for all other pollutants are averages reported in References 5-23 and 5-50.
Flame Retention Burner Head	20-40	26-88	11-22	0.2-1.8	2.0	NA	80-83	NA	\$52[e]	If new burner is needed as well as a burner head, the total cost would be \$385. Cost is for 1978-79 heating season.
Controlled Mixing Burner Head by EPA/ Rocketdyne	10-50	34	13	0.7-1.0	less than 1.0	NA	80	NA	\$43[e]	Cost of mass produced burner head only about \$1.50. Combustible emissions are relatively low because hot firebox was used.
Integrated Furnace System by EPA/ Rocketdyne	20-30	19	20	1.2	less than 1.0	NA	84	74	\$250 over conventional furnace	Uses optimized burner head. For new furnace installation only. Combustible emissions are higher than with burner head because of quenching in air cooled firebox. Recent cost estimate.
Blueray "blue flame" Burner/Furnace System	20	10	4.5-7.5	1.5-2.5	zero	NA	84	74	\$100 over conventional furnace	New installation only. Furnace is commercially available. Recent cost estimate.
M.A.N. Burner	10-15	10-25	less than 30	NA	less than 1.0	NA	85	NA	NA	Both for retrofit or new installations. Not yet commercially available in U.S. Commercialization expected in 1980.

[a] Sum of NO and NO_2 reported as NO_2
[b] Unburned hydrocarbons calculated as methane (CH_4)
[c] Typical costs of uncontrolled unit \$650-\$1,000
NA = Not available.
[e] Original costs reported for years other than 1978 were corrected for inflection using Gross National Product (GNP) implicit price deflectors (Reference 5-51).

The most effective NO_x controls for new residential oil burning is to use the Rocketdyne/EPA furnace system, the Blueray "blue flame" furnace and the M.A.N. burner. Average NO_x emission reductions with these controls range from 65 to about 80 percent depending on which uncontrolled emission level is considered (i.e., 55 ng/J from Reference 5-23 or 61 ng/J from Reference 5-50). Both the flame retention and Rocketdyne/EPA controlled mixing burner head are desirable features for retrofitting existing furnaces because they also allow for more efficient furnace operation with lower combustible and smoke emissions. The controlled mixing burner head results in a modest NO_x reduction of 20 percent. Although most flame retention head burners produce high NO_x emissions, a few result in some decrease in NO_x from baseline levels.

The Blueray furnace is the only equipment available commercially in the U.S. The M.A.N. burner is commercially available only in Europe. However, this low-NO_x advanced burner is expected to enter the U.S. market in less than 1 year. The range in NO_x emissions for the M.A.N. burner reflects test data reported for two firing configurations. The lower emission factor was obtained with an air cooled blast tube while the high emission factor is for an uncooled blast tube. The M.A.N. warm air furnace system utilizes a cooled blast tube and firebox for low-NO_x emissions and high heat transfer efficiency. The M.A.N. burner is an attractive control technique because it may be applicable to existing units.

The Rocketdyne/EPA warm air furnace is still undergoing field tests to further demonstrate its reliability and improved performance. Presently, however, Rocketdyne has no immediate plans to market the optimized furnace design. As Table 5-6 indicates, CO, UHC, and smoke emissions are equally reduced with any of the NO_x control equipment available. Similarly, thermal efficiencies are improved reducing fuel consumption and seasonal pollutant emissions. Due primarily to its commercial availability and low incremental cost, the Blueray furnace is considered the best available technology for new distillate oil-fired residential warm air furnaces.

Table 5-6 summarizes the various control techniques available for CO, UHC, smoke and particulate emission reduction from existing warm air furnaces, water heaters, or hydronic boilers burning distillate oil.

TABLE 5-6. PERFORMANCE SUMMARY OF CONTROLS FOR REDUCTION OF SEASONAL COMBUSTIBLE, SMOKE AND PARTICULATE EMISSIONS FROM OIL-FIRED RESIDENTIAL HEATERS

Control	Percent Reduction (Average)				Percent Improvement in Fuel Saving	1978 Installed Control Cost	Comments
	CO	UHC	Smoke	Particulates			
Replacement of worn-out units	(65)	(87)	NC[a]	(17)	NA[b]	\$650-1000[c] for new warm air furnaces	Nine percent of the existing residential heaters were found in need of replacement. Recent cost estimates.
Tuning and scheduled seasonal maintenance	(16)	(3.0)	(59)	(7.0)	1.7 percent average efficiency increase	\$38-60[c]	Tuning results in an increase in efficiency for some units and a decrease in efficiency for others.
Delayed action solenoid valves	NA	NA	60-90 (80)	NA	NA	\$43[c]	Smoke emission reduction primarily during start-up and shut-down.
Reduced excessive firing capacity with conventional burner	(14)	NA	10-38 (24)	(3.7)	5.6-2.5 (14)	\$52[c]	Installation of flame retention head cone plus modifications to reduce firing capacity by about 36 percent.
Reduced excessive firing capacity with new retention burner	(14)	NA	80-85 (82)	(3.7)	14-39 (30)	\$385[c]	Installation of new lower capacity burner with flame retention head. Firing capacity reduced by 43 percent.
Installation of positive chimney dampers	2.0-19 (11)	NA	NA	2.2-17 (10)	3-9	\$200[c]	Large variation in pollutant emission reduction due to changes in furnace cycle frequency. Recent cost estimates
Increased thermostat anticipator setting	41-45 (43)	NA	NA	31-33 (33)	0-2	Minimal	Very effective for residential units with high cyclic efficiency
Overnight thermostat cut-back (3-5K)	9.1-27 (17)	NA	NA	12-24 (15)	7-15	Minimal	Cost does not take into account improved home insulation which might be necessary with thermostat cut-back.

[a] NC = No change

[b] NA = Not available

[c] Costs for material and labor are typical of New England area. Original costs reported for years other than 1978 were corrected for inflation using Gross National Product (GNP) implicit price inflectors (Reference 5-51)

Parenthesis indicate arithmetic averages

Again, the data in this table reflects primarily emissions data from warm air furnaces but these controls are equally applicable to other residential heating equipment.

The first two techniques listed, replacement and tuning with scheduled maintenance of existing furnaces, are aimed at reducing combustible and smoke emissions and increasing system efficiency. These controls have essentially no effect on NO_x emissions. However, CO, and UHC emissions are significantly reduced just by replacing worn-out units. Smoke emissions are reduced significantly by tuning the equipment on a yearly basis. This indicates that most of the yearly combustible and smoke emissions from oil-fired residential heaters are caused by very old units in need of replacement or units in need of maintenance or tuning. Delayed action solenoid oil valves reduce smoke emissions during start up and shut down periods when smoke as well as CO and UHC emissions are highest.

The remaining control alternatives indirectly achieve a yearly reduction in NO_x emissions firstly, through reduced equipment usage and secondly, through improved fuel efficiency. However, these controls are aimed primarily at lowering seasonal combustible emissions and reducing yearly fuel consumption. Reduced excessive firing capacity and change in thermostat anticipator setting to increase furnace on-time lower combustible emissions by reducing cyclic frequency of the furnace. These controls lowered CO emissions by 14 to 43 percent respectively and smoke 24 and 82 percent primarily by reducing seasonal number of on-off cycles.

In general, these alternative control techniques are very effective in reducing the annual combustible and smoke emissions from residential oil-fired furnaces. With the exception of reducing excessive firing capacity which might cause some operational problems with nozzle plugging, all control alternatives are available to the consumer. Because all reduce fuel consumption through improved efficiency or directly by reducing equipment usage, there are some cost benefits as well as environmental benefits associated with these controls.

5.5 EMISSION CONTROL ALTERNATIVES FOR COMMERCIAL SYSTEMS

5.5.1 Commercial Heaters

Application of control technology to commercial heating equipment is very limited. No information was found for low emission systems in indirect gas-fired equipment although there is a strong interest in high efficiency appliances which implies lowest excess air and complete combustion. Compared to residential gas-fired equipment, a greater percentage of commercial warm air heaters or duct heaters utilize a forced combustion air burner as opposed to a naturally aspirated burner. These power burners usually have greater flexibility for excess air control while maintaining low CO and UHC emissions.

Theoretically, the flame quenching and surface combustor concepts of the gas-fired residential burners could be implemented for commercial systems. For oil-fired equipment, the EPA/Rocketdyne residential burner head design implementing 25 degree air swirler vanes combined with optimum choke diameter (varying as the 0.4 power of the oil flow) was found to minimize NO_x emissions from burners with oil flow capacity as high as 12.6 ml/s (12 gph). NO_x emissions with this burner design were generally 25 to 50 percent lower than those from commercially available burners with or without flame-retention devices and operating under similar conditions (Reference 5-52).

Combustible emission controls listed in Table 5-6 could also be applied to commercial space heating equipment. For example, reducing firing rate would be a viable alternative for commercial heating systems where the demand is strongly cyclic. Additionally, increased thermostat anticipator setting or overnight thermostat cut-back could reduce annual emissions by amounts equal to those obtained for residential units.

5.5.2 Commercial Boilers

Commercial or small industrial boilers are mostly single burner packaged firetubes. NO_x control techniques for small firetubes with heat input capacities less than 2.9 MW (10×10^6 Btu/hr) have not been widely investigated. However, the similarity in equipment design between the small firetubes and the larger industrial size firetubes may allow application of similar combustion modification control techniques. Control techniques investigated for industrial boilers which may be applicable to the small commercial firetube units are listed in Table 5-7. Although NO_x reductions represent controlled levels achieved with both industrial firetubes and watertube designs, as well as field erected and packaged boilers, it may be possible that these NO_x reductions could also be achieved with small commercial firetubes.

TABLE 5-7. COMBUSTION MODIFICATION NO_x CONTROLS FOR OIL- AND GAS-FIRED INDUSTRIAL BOILERS (Reference 5-22)

Control Technique	Description of Technique	Effectiveness of Control (Percent NO_x Reduction)			Range of Application	Comments
		Residual	Distillate Oil	Natural Gas		
None	Baseline	67-362 ng/J	45-107 ng/J	29-28 ng/J	Average excess O_2 measured 5.8 percent	Emissions are from firetube and watertube boilers not equipped with preheaters.
Low Excess Air (LEA)	Reduction of combustion air	0-28; 11 average or 10 ng/J/% O_2 reduction	0-24; 11 average or 10 ng/J/% O_2 reduction	71% decrease to 85% increase (10% average reduction)	Generally excess O_2 can be reduced to 2.5% representing a 3% drop from baseline	Added benefits included increase in boiler efficiency. Limited by increase in CO, HC, and smoke emissions
Staged Combustion Air	Fuel rich firing burners with secondary combustion air ports	20-50	17-44	5-46	70-90% burner stoichiometries can be used with proper installation of secondary air ports	Best implemented on new units. Retrofit is probably not feasible for most units. Generally less effective for gas-fired units. Doubtful application.
Flue Gas Recirculation (FGR)	Recirculation of portion of flue gas to burners	15-30	58-73	48-86	Up to 25-30% of flue gas recycled. Can be implemented on all design types	Best suited for new units. Costly to retrofit. Possible flame instability at high FGR rates. Most effective on watertube units
Flue Gas Recirculation plus staged combustion	Combined techniques of FGR and staged combustion	25-53	73-77	Up to 76	Max. FGR rates set at 25% for distillate oil and 20% for residual oil	Retrofit may not be feasible. Best implemented on new units. Doubtful application of staged combustion.
Load Reduction (LR)	Reduction of air and fuel flow to all burners in service	33% decrease to 25% increase	31% decrease to 17% increase	32% decrease to 82% increase (10% average reduction	Applicable to all boiler types and sizes. Load can be reduced to 25% of max. Better implemented with improved firebox design	Technique not effective when it necessitates an increase in excess O_2 levels, LR possible implemented in new designs as reduced combustion intensity (enlarged furnace plan area)
Low-NO_x Burners (LNB)	New burner designs with controlled air/fuel mixing and increased heat dissipation	20-50	20-50	20-50	New burners generally applicable to all boilers. More specific information needed	Specific emissions data from industrial and commercial boilers equipped with LNB are lacking

Available control alternatives include low excess air, flue gas recirculation and load reduction. Low excess air is the only control technique generally in use with boilers in this size category. Low-NO_x burners, if developed, could be the most cost-effective NO_x control technique besides LEA operation.

Table 5-8 summarizes NO_x control techniques which have been investigated for industrial stoker coal-fired boilers. These controls could also be potentially applicable to commercial size stokers. However, as indicated, NO_x reduction performance data are very limited for commercial boiler equipment in the size category of less than 2.9 MW (10×10^6 Btu/hr) heat input capacity.

TABLE 5-8. COMBUSTION MODIFICATION NO_x CONTROLS FOR STOKER COAL-FIRED INDUSTRIAL BOILERS (Reference 5-22)

Control Technique	Description of Technique	Effectiveness of Control (Percent NO_x Reduction)	Range of Application	Comments
None	Baseline	150 ng/J	Excess O_2 measured 6.6-9.4%	Emissions are underfeed stokers characteristic of low capacity stoker-fed boilers.
Low Excess Air (LEA)	Reduction of airflow under stoker bed	5-25	Excess O_2 limited to 5-6% minimum	Danger of overheating grate, clinker formation, corrosion, and high CO emissions
Staged Combustion (LEA + OFA)	Reduction of under grate airflow and increase of overfire airflow	5-25	Excess O_2 limited 5% minimum. Most stokers have OFA ports as smoke control devices but may need better airflow control for NO_x reduction	Need research to determine optimal location and orientation of OFA ports for NO_x emission control. Overheating grate, corrosion and high CO emission can occur if under grate airflow is reduced below acceptable level as in LEA
Reduced Load	Reduction of coal and air feed to the stoker	Varies from 49% decrease to 25% increase in NO_x (average 15% decrease)	Has been used down to 25% load	Only for stokers that can reduce load without increasing excess air. Not a desirable technique because of loss in boiler efficiency

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SECTION 6

ENVIRONMENTAL ASSESSMENT

The majority of residential and commercial heating systems burn natural gas and fuel oil; thus the primary environmental impact of these sources is on ambient air quality. Solid waste streams come from residential and commercial wood- or coal-fired equipment, but these units constitute a very small portion of the total number of existing residential and commercial heating equipment. This may change, however, due to the recent increase in wood burning equipment throughout the U.S. Although, residential warm air furnaces and commercial hot water or steam boilers contributed each approximately 2.0 percent of the total manmade NO_x emissions in 1977, their impact on ambient NO_x levels in urban areas is more significant than these percentages indicate (Reference 6-1). The seasonal usage pattern, the low stack heights and spatial density are the principal factors which contribute to a disproportionate impact of residential and commercial heating systems on ground level ambient NO_2 concentration during the cold winter season. The main focus of this section will be on assessing the environmental impact of NO_x emissions control for residential and commercial heating systems on ambient air pollutant levels.

The environmental assessment begins with a discussion of results from a recent field test to quantify multimedia emissions from a Blueray low-NO_x high-efficiency residential warm air furnace. This furnace is considered best available NO_x control technology for domestic oil-fired control warm air furnaces. The assessment then discusses ambient air impacts of the other NO_x controls identified in Section 5. The operational, maintenance, and cost impacts of these controls are then summarized followed by an evaluation of data base and future needs.

6.1 ENVIRONMENTAL IMPACT ANALYSIS

Table 6-1 summarizes level 1 analysis results of exhaust emissions from a Blueray low-NO_x high- efficiency home furnace in the field. This furnace was recently tested as a part of the NO_x EA program to quantify the environmental impact of low-NO_x residential systems (Reference 6-2). Table 6-1 also summarizes air pollutants from five conventional (uncontrolled) oil-fired residential warm air furnaces and two oil-fired hot water heaters tested in another EPA sponsored test program (Reference 6-3). As indicated, for the Blueray unit two furnace operating conditions were investigated; continuous operation and a 10-minutes on/10-minutes off cyclic operation. Tests performed on the conventional oil-fired units were mostly with 50-minutes on/10-minutes off cycles. However, two oil-fired systems were also tested with a 10-minute on/20-minute off cycle to study the effect of cycle mode on organic emissions.

Although emissions for any one pollutant vary significantly between test programs and test conditions, several trends are evident from the data in Table 6-1. For example, for the Blueray furnace CO, HC and organic emissions (POM) increased when the furnace operation cycled. The contribution of combustible emissions during ignition and shutoff periods is clearly evident here. The average NO_x emissions decreased in the cyclic operating mode primarily due to lower combustor temperatures. Trace elements and particulate emissions generally remained unchanged when the furnace was switched to cyclic operation. However, emissions of Fe, Ni, and possibly Cr, Mn, and Mo were noticeably higher for continuous furnace operations. The higher concentrations of these trace elements during continuous firing may be partly attributed to deterioration of iron and steel surfaces internal to the furnace and partly to contamination of samples during sampling and analysis. Sulfur oxides (SO_2 and SO_3) emissions from the Blueray furnace are questionable because a sulfur balance analysis indicated only 30 to 40 percent conversion of fuel sulfur to oxides.

For conventional furnaces, total organic emissions were about 20 percent higher than those from the Blueray unit operating intermittently. In addition, particulate emissions were higher for the

TABLE 6-1. CRITERIA TRACE ELEMENTS AND ORGANIC EMISSIONS FROM CONVENTIONAL AND LOW-NO_x OIL-FIRED HEATERS

Conventional Heaters[a]			Blueray Low-NO_x Furnace		
Pollutant	Emissions -- Cyclic Measurement ng/J[b]	Test Method and Operation, Techniques	Emissions -- Continuous Operation, ng/J[b]	Emissions -- Cyclic Operation, ng/J[b]	Test method and Measurement Techniques
Part	3.1	SSMS	0.87-1.32	0.82-1.30	SASS -- Method 5
SO_2	--	ND	26.9	35.5	EPA Method 8
SO_3	5.9	CC	0.2	1.0	EPA Method 8
NO_x	--	ND	10	7	Chemiluminescent
CO	--	ND	9	59	NDIR
Smoke	1.0	--	--	--	ND
HC	--	ND	0	5	FID
Organic	9.2	GC/MS	0.38	7.63	GC
Aluminum	0.25	SSMS	--	--	ND
Antimony	0.0057	SSMS, AAS	< 0.0005	< 0.0006	AAS
Arsenic	0.0015	SSMS, AAS	< 0.0006	< 0.0007	AAS
Barium	0.016	SSMS	< 0.011	< 0.0147	AAS
Beryllium	--	ND	$< 1.54 \times 10^6$	$< 1.79 \times 10^5$	ND
Bismuth	--	ND	< 0.0008	< 0.0008	AAS
Boron	--	ND	< 0.0039	< 0.0130	Colorimetric
Cadmium	0.011	SSMS	< 0.0022	< 0.0014	AAS
Calcium	0.45	SSMS	--	--	ND
Chromium	0.029	SSMS	< 0.1104	< 0.0072	AAS
Cobalt	--	ND	< 0.0088	< 0.0074	AAS
Copper	0.16	SSMS	0.0191	0.0149	AAS
Iron	0.14	SSMS	0.542	0.0594	AAS
Lead	0.042	SSMS	< 0.027	< 0.0278	AAS
Magnesium	0.21	SSMS	--	--	ND
Manganese	--	ND	< 0.0152	< 0.0033	AAS
Mercury	0.0012	AAS	< 0.0054	< 0.0039	ND
Molybdenum	--	ND	< 0.0144	< 0.0046	AAS
Nickel	0.29	SSMS	< 0.0882	< 0.0139	AAS
Potassium	0.23	SSMS	--	--	ND
Selenium	--	ND	< 0.0030	< 0.0023	AAS
Tellurium	--	ND	< 0.0009	< 0.0010	AAS
Thallium	--	ND	< 0.0482	< 0.0533	AAS
Tin	--	ND	< 0.0009	< 0.0012	AAS
Titanium	--	ND	< 0.0033	< 0.0013	AAS
Vanadium	0.0029	SSMS	0.0008	< 0.0014	AAS
Zinc	0.11	SSMS	0.0042	0.0037	AAS

[a] Average of five warm air furnaces and two hot water heaters all using conventional high pressure burners

[b] ng/J on a heat input basis

SASS	=	Source Assessment Stack Sampler modified
CC	=	Controlled Condensation, a Goksoyr-Ross procedure
SSMS	=	Spark Source Mass Spectroscopy
GC/MS	=	Gas Chromatography/Mass Spectroscopy
ND	=	Not determined
AAS	=	Atomic Absorption Spectrometry
NDIR	=	Nondispersive Infrared Analyzer (continuous monitoring)
FID	=	Flame Ionization Detector (continuous monitoring)

conventional units. These observations substantiate that the low-NO_x unit is also a high-efficiency unit.

Trace element emissions between the two test programs showed few significant differences. These results indicate that trace element emissions are not generally increased when using the Blueray furnace compared to conventional heating equipment.

Trace element measurements were performed primarily using the Spark Source Mass Spectroscopy (SSMS) for the conventional heaters, while Atomic Absorption Spectrometry (AAS) was predominantly used for the Blueray furnace. Because of the low level of mineral matter in the distillate fuel oil and the small amount of particulate matter collected, several trace elements were present below detectable levels (indicated by the "<" sign) when using the AAS analytical method during the Blueray tests. SSMS analysis of mineral matter in the distillate fuel oil burned in the conventional heaters indicated that for over 50 percent of the elements, stack emissions were below 70 percent of levels entering the heaters. This finding may indicate some retention of fuel oil mineral matter in residential heating equipment.

6.2 SOURCE ANALYSIS MODEL EVALUATION

To help quantify the environmental impact of a low-NO_x residential furnace a Source Analysis Model, SAM IA (Reference 6-4), was applied to the flue gas data from the fifth Blueray unit tested in the NO_x EA program. IERL and the conventional units tested by GCA have been developing a series of Source Analysis Models to compare emission data to environmental objectives, termed Multimedia Environmental Goals (MEGs) (Reference 6-5). The model selected for the level of detail obtained from the Blueray tests was SAM IA, designed for rapid screening purposes. As such, it includes no treatment of pollutant transport or formation. Goal comparisons employ threshold effluent stream concentration goals, termed Discharge Multimedia Environmental Goals (DMEGs).

For the purposes of screening pollutant emissons data to identify species requiring further study, a Discharge Severity (DS) is defined as follows:

$$DS_i = \frac{\text{Concentration of Pollutant i in Effluent Stream}}{\text{DMEG of Pollutant i}}$$

The DMEG value, the threshold effluent concentration, is the maximum pollutant concentration considered safe for occupational exposure. When DS exceeds unity, more refined chemical analysis may be required to quantify specific compounds present.

To compare waste stream potential hazards, a Weighted Discharge Severity (WDS) is defined as follows:

$$WDS = (\Sigma_1 \, DS_i) \times \text{Mass Flow Rate},$$

where the Discharge Severity is summed over all species analyzed. The WDS is an indicator of output of hazardous pollutants and can be used to rank the needs for controls for waste streams. It can also be used as a preliminary measure of how well a pollutant control, say a combustion modification NO_x control, reduces the overall environmental hazard of the source. An extensive exposition of SAM IA and list of DMEGs are presented in Reference 6-4 and will not be repeated here.

SAM IA was used to evaluate the emissions data in Table 6-1. Since the model requires effluent concentrations on a mass per volume basis, the emission factors in Table 6-1 were converted to concentrations at a furnace discharge vent assuming a flue gas dilutive to 17 percent O_2. This O_2 level was the average roof vent level reported in Reference 6-3. Table 6-2 lists discharge severities for those species with DS greater than 0.1. In calculating DS for NO_x, SO_2, and CO for the conventional furnace emission factors taken from AP-42 (Reference 6-5) were used, since field tests reported in Reference 6-3 did not measure these pollutants.

The data in Table 6-2 led to several conclusions. First, DS values for trace elements between the units are quite comparable as expected based on trace elements emission results presented in Table 6-1. Of the trace elements Cr and Ni emissions present the greatest potential hazard in all cases. However, measured levels of these metals may be an artifact of the stream sampling methodology. The flue gas sampling trains in both the conventional furnace test program and the NO_x EA contained many stainless steel components. Thus, some of the reported Cr and Ni could have come from the sampling train itself rather than being a significant component of the flue gas.

For both types of units SO_2 emissions were flagged and emissions of certain organic categories had DS values greater than 1. For the

TABLE 6-2. FLUE GAS DISCHARGE SEVERITIES GREATER THAN 0.1 FOR THE BLUERAY FURNACE AND CONVENTIONAL OIL-FIRED HEATERS

Pollutant	Blueray Furnace (Reference 6-2)		Conventional Furnace (Reference 6-3)
	Continuous Operation	Cyclic Operation	Cylic Operation
NO_x	0.86	0.60	4.7[a]
SO_2	1.6	2.1	6.3[a]
SO_3	0.15	0.77	4.5
CO	0.17	1.1	0.30[a]
Arsenic (As)	0.23	0.27	0.60
Cadmium (Cd)	0.17	0.11	0.85
Chromium (Cr)	85	5.5	22
Cobalt (Co)	0.14	0.11	ND[b]
Copper (Cu)	0.075	0.055	0.60
Iron (Fe)	0.42	0.046	0.011
Lead (Pb)	0.14	0.14	0.21
Nickel (Ni)	4.5	0.73	15
Thallium (Tl)	0.37	0.41	ND[b]
Amines	NF[c]	NF[c]	1.6
Carboxylic acid	0.20	2.3	--
Total Stream DS	95.7	15.5	59.0

[a] Pollutant not measured in test program, DS calculated from AP-42 emission factors: NO_x; 55 ng/J; SO_2; 100 ng/J; CO; 15 ng/J

[b] ND: Species not analyzed for

[c] NF: None found

conventional units amines were flagged as being of potential concern; for the Blueray unit carboxylic acids would be of potential concern under cyclic operation. The DS for NO_x exceeds 1 for conventional units, but is less than 1 for the low-NO_x Blueray unit under both continuous and cyclic operations.

In summary, flue gas stream Total Discharge Severity (TDS) for typical conventional units appears to fall between the TDS for the low-NO_x unit under cyclic (normal) operation and that for the low-NO_x unit under continuous operation. If Cr and Ni are removed from the TDS calculations, adjusted TDSs of 22, 6.2, and 9.3 result for the conventional, Blueray continuous, and Blueray cyclic data respectively. Thus, if measured Cr and Ni indeed comes from the sampling train, then the low-NO_x unit's TDS under both cyclic and continuous operation is lower than that of the conventional units. This suggests that using the Blueray design to control NO_x from oil-fired heating units is environmentally sound.

Of the flue gas species, SO_2 had the largest DS value. Its potential hazard was lower for the low-NO_x unit than for the conventional units (based on an AP-42 emission factor for conventional units), however, this is most likely due to poor sulfur emissions test results for the Blueray unit and fuel composition changes, rather than a consequence of low-NO_x design. SO_3 emissions were also flagged as of concern for the conventional units. The fuel sulfur to SO_3 conversion for two conventional domestic heaters was reported to range between 2.1 and 6.5 percent (Reference 6-3). This relatively high conversion rate for distillate oil combustion was attributed to high combustion excess air levels (Reference 6-3). The DS for SO_3 is lower for the low-NO_x unit (again, probably uncertain due to Blueray test results as well as fuel composition effects).

The DS for NO_x was significantly lower for the Blueray furnace, decreasing from a value of about five for conventional units (representing potential environmental hazard), to less than one for the low-NO_x unit.

Finally, the flue gas stream total DS for the low-NO_x unit under cyclic (or "normal") operation was lower than that for conventional units, due in part to significant NO_x reductions. However, the Blueray furnace DS under continuous operation was higher, due largely to significantly increased Cr emissions.

6.3 ENVIRONMENTAL IMPACTS OF NO_x CONTROLS ON CRITERIA POLLUTANTS

With the exception of radiant screens and secondary air baffles for natural gas-fired residential burners the NO_x control techniques for either gas-fired or oil-fired residential heaters have essentially no adverse impact on other criteria and total organic pollutants. On the contrary, some of the low-NO_x high-efficiency combustor designs such as the Blueray and the M.A.N. burners, assure low combustible emissions by recirculating the combustion products. The flue gas recirculation of the Blueray combustor results in very low CO, UHC and smoke emissions even at relatively low excess air operation. The low excess air also improves thermal efficiency and reduces seasonal fuel consumption. Other effective NO_x controls such as the EPA/Rocketdyne furnace, the M.A.N. burner for fuel oil and the Amana HTM for natural gas are also effective in reducing combustible emissions while significantly lowering NO_x.

Table 6-3 summarizes the level of NO_x control achievable with most effective control alternatives for both gas- and distillate oil-fired residential heaters. Control alternatives which are far from commercialization have not been included. The data indicate that the flame retention burner head, for example, could be used to achieve a NO_x standard for distillate oil-fired warm air furnaces of 40 ng/J heat input or approximately 50 ng/J of useful heat. For more stringent NO_x standards for oil-fired heaters the EPA/Rocketdyne burner head and the Blueray design can achieve 35 and 15 ng/J on a heat input basis (11.5 and 4.9 lb/1000 gal of oil) respectively. For natural gas-fired heaters the modulating furnace and the Amana HTM combustor could achieve NO_x standards of 25 and 10 ng/J on a heat input basis (920 and 390 ng/m^3 of gas) respectively.

With the exception of the South Coast Air Quality Management District (SCAQMD) in Southern California, there are no promulgated regulations governing NO_x emissions from residential heaters. Rule 1111 of the SCAQMD states that all natural gas-fired residential warm air furnaces for stationary residences sold after January 1, 1984, must not

TABLE 6-3. ENVIRONMENTAL IMPACT OF MOST EFFECTIVE NO_x CONTROL ALTERNATIVES ON RESIDENTIAL SPACE HEATERS

Emission Level				Environmetal Impact[a] Percent Change in Emissions			Application
ng/J Heat Input	ng/J Heat Output or Useful Heat	Fuel	Best Control Alternative	CO	UHC	Smoke	R -- Retrofit N -- New
40[b]	50	Distillate oil	Flame retention burner head	-47	-78	-38	N, R
35	45	Distillate oil	EPA/Rocketdyne burner head	-57	-80	-78	N, R
19	29	Distillate oil	EPA/Rocketdyne furnace	-33	-73	-90	N
15	20	Distillate oil	Blueray Furnace	-80	-56	-100	N
			M.A.N. Burner	N/A	N/A	-70	N, R
25	35	Natural gas	Modulating furnace	N/A	N/A	--	N
10	12	Natural Gas	Amana HTM Combustor	N/A	N/A	--	N

[a] Percent reductions are based on baseline NO_x emissions data reported in Reference 6-6 and average controlled levels reported in Section 5 of this report.

[b] Lowest NO_x level measured from a flame retention burner (Reference 6-7).

exceed 40 ng/J of useful heat (the thermal heat output of a system). Brookman and Kalika measured uncontrolled NO_x levels from existing gas-fired heaters at about 60 ng/J of heat input (Reference 6-6). This emission level translates to about 85 ng/J of useful heat for a furnace cycle efficiency of 70 percent. Thus the SCAQMD Rule 1111 requires more than 50 percent NO_x reduction from uncontrolled levels. As indicated in Table 6-3, both the modulating furnace and the HTM combustor can meet this regulation. Furthermore, the commercial development of the Bratko burner could in the near future add one more control alternative capable of meeting stringent NO_x regulations for natural gas-fired heaters.

Table 6-3 also shows the effect of NO_x controls on other criteria pollutants. As indicated, there are substantial reductions of combustible emissions from distillate oil-fired space heaters for each of the NO_x control alternatives listed. These percent reductions were calculated using the cyclic emission levels suggested by Barrett et al. as being representative of existing residential oil-fired heaters (Reference 6-8). These suggested uncontrolled combustible emissions, however, account for equipment in need of tuning. Therefore, tuning, maintenance and other controls discussed in Section 5 (see Table 5-7) could also reduce these combustible emissions lowering the percent reductions of Table 6-3 substantially. However, it can be generalized that selected most effective NO_x control alternatives also reduce overall seasonal combustible emissions as well as lowering NO_x.

6.4 OPERATIONAL AND COST IMPACTS OF CONTROLS

NO_x controls listed in Table 6-3 for both natural gas and distillate oil-fired residential heaters not only reduce NO_x and combustible emissions but often bring about an improvement in equipment operating performance. For example for oil-fired equipment, both the Blueray and the EPA/Rocketdyne furnace design have shown an improvement in seasonal thermal efficiency of at least 10 percent above that of conventional warm air furnaces. The Blueray furnace shows no loss in performance and maintains minimum smoke and combustible emissions (Reference 6-9). Similarly, the recently developed EPA/Rocketdyne furnace has demonstrated relatively steady performance over an average field test period of 2 months (Reference 6-10). Furthermore, representatives of the

M.A.N. burner claim that the thermal efficiency and overall performance of their system does not deteriorate thus the burner does not require yearly servicing as do conventional oil- fired residential heaters (Reference 6-11). However, field tests have not yet been performed to verify these claims.

Table 6-4 lists the cost data available for the NO_x control alternatives discussed throughout this report for residential heating systems. Since no cost data are available on the M.A.N. burner either for a retrofit or new installation this control has not been listed. As indicated, retrofit of the optimized burner head for residential oil-fired warm air furnaces represents the most cost-effective alternative to achieve a NO_x emission level of about 45 ng/J of useful heat. The payback period for the initial investment of $43 is estimated at less than one year. Retrofit of the flame retention burner head to achieve NO_x emissions of about 50 ng/J of useful heat from existing furnaces is the second most effective control alternative for this level of control. Payback period is also estimated at less than one year. For a stringent NO_x emission control level of about 20 ng/J of useful heat for new oil-fired heaters the Blueray "blue flame" furnace is the most cost-effective as well as the only commercially available alternative.

The payback periods listed in Table 6-4 are estimates based on the time required to recover the money spent for the initial investment of installing NO_x control equipment. Since all these control alternatives bring about an increase in thermal efficiency, and thus fuel savings, the control is often paid for with the fuel cost savings cummulated over a time period less than a year. It should also be pointed out that for new equipment installed in new homes the cost of the furnace is generally included with that of the house. The incremental cost of the furnace is then annualized over the mortgage period of the house (i.e., 20 to 30 years). For example, the estimated $100 incremental cost of a Blueray furnace would be annualized to about $11 per year for a 20 year mortgage at 9.25 percent interest. It can be seen that the annual fuel savings, $100 for a typical oil bill of $500/year (Reference 6-9) would more than compensate for the $11 increase in annual mortgage rate.

TABLE 6-4. COST IMPACT OF NO_x CONTROL ALTERNATIVES

Control	Fuel	Achievable NO_x Level ng/J Useful Heat	1978 Incremental Investment Cost	Cost Effectiveness \$/(ng/J)[a]	Payback Period Based on Annual Fuel Bill of \$500
Amana (HTM) Furnace	Natural Gas	12 (390 ng/m^3gas)	\$100-\$300 over cost of conventional furnace	1.7-5.2	1-3 years
Modulating Furnace	Natural Gas	35 (920 ng/m^3 gas)	\$50-\$250 over cost of conventional furnace	1.4-7.0	1-3.8 years
Surface Combustion Burner (Infrared Bratko type)	Natural Gas	12 (39 ng/m^3 gas)	\$100-\$200 over cost of conventional furnace/heater	1.7-3.4	3.5-8.0 years
Pulse Combustion Burner[b]	Natural Gas	21 (683 ng/m^3 gas)	\$300-\$600 over cost of conventional furnace/heater	6.1-12.2	1.7-3.5 years
Catalytic Combustion Burner[b]	Natural Gas	Estimated 5 (163 ng/m^3 gas)	\$150-\$250 over cost of conventional furnace/heater	2.3-3.9	1.4-2.3 years
Flame Retention Burner Head	Distillate Oil	50 (1.8 g/kg fuel)	\$52 -- retrofit including installation	2.6	Less than 1 year
Flame Retention Burner	Distillate Oil	50 (1.8 g/kg fuel)	\$385 -- retrofit of reduced capacity burner	12.8	3.5 years
EPA/Rocketdyne Burner Head	Distillate Oil	45 (1.6 g/kg fuel)	\$43 -- retrofit including installation	1.3	Less than 1 year
EPA/Rocketdyne Furnace	Distillate Oil	29 (0.9 g/kg/fuel)	\$250 over cost of conventional furnace	4.2	2.5 years
Blueray Furnace	Distillate Oil	20 (0.7 g/kg fuel)	\$100 over cost of conventional furnace	1.7	1 year

[a] Based on uncontrolled NO_x emissions of 70 ng/J heat output for natural gas-fired heaters and 80 ng/J heat output for distillate oil-fired heaters. Cost-effectiveness is based on the differential investment cost of the control.

[b] Based on installation on a condensing system where seasonal efficiencies can be as high as 95 percent.

6.5 DATA BASE EVALUATION AND NEEDS

The review of published papers on residential and commercial heating systems conducted in this study has revealed a substantial amount of criteria emissions data for gas- and oil-fired residential heaters. Recently, noncriteria pollutants (trace elements and organics) have also been measured. Residential equipment has been extensively characterized and inventories are well documented. In addition, few control alternatives for NO_x and combustible pollutants have also been investigated. Some low-NO_x and high-efficiency furnace designs are commercially available, while other equally or more effective designs are either in final demonstration stages or await commercialization. Performance data on these improved heating equipment designs are being gathered through EPA sponsored field and laboratory programs. These and other test programs will aid in further documenting the performance, reliability of these advanced sources and quantifying their impact on other pollutant emissions.

This general availability of emissions and NO_x control technology data for residential warm air furnaces is contrasted by the purity of inventory and emission test data for commercial space heating equipment with heat input generally less than 0.3 MW (10^6 Btu/hr).

These units include rooftop commercial heating equipment, both indirect and direct fired, which are often combined with air conditioning systems, and a number of indoor waters. The impact of these sources needs to be identified through a detailed inventory of existing equipment and a review of use patterns and fuel consumptions.

These commercial space heating sources could be substantial contributors to ambient NO_2 concentrations during the cold season. With the exception of the EPA/Rocketdyne low-NO_x burner head design for commercial size oil-fired burners little NO_x control technology has been developed. Although combustion equipment in this source category is generally similar to the residential equipment, the assumption that low NO_x burner systems may be applicable to commercial units is only speculative at present. Other low NO_x design concepts such as flue gas recirculation as used in the Blueray furnace and M.A.N. burners can probably be scaled up to commercial size equipment. In fact, the M.A.N.

burner is being scaled up to 0.45 MW (1.5 x 10^6 Btu/hr). A unit is being tested in W. Germany (Reference 6-11).

Information on NO_x control alternatives for commercial size steam and hot water boilers burning gas or oil is also scarse. While it can be speculated that some boiler designs lend themselves to NO_x control techniques investigated for industrial size boilers, little experimental data exist to confirm this. Furthermore, low-NO_x burner technology for heat input capacities in the size range of 0.1 to 2.9 MW (0.4 to 10 x 10^6 Btu/hr) show promise based on advanced burner technology developed for both residential units on the small side and industrial units on the large side. For example, the TRW oil-fired low-NO_x burner (Reference 6-12) with a capability of reducing NO_x up to 50 percent while increasing fuel efficiency is being demonstrated on industrial size boilers. However, the low-NO_x design concept of this burner can apparently be scaled down to capacities less than 2.93 MW (10 x 10^6 Btu/hr). Lack of regulatory incentives for commercial size boilers has suppressed efforts in this area however.

In the area of solid fuel-fired residential and commercial equipment NO_x technology is also very limited. Past and on-going test programs have mainly dealt with quantifying the pollutant levels and identifying equipment operating parameters and fuel characteristics which have some impact on these levels. Primary pollutants of interest for this category of equipment have been particulate and smoke emissions as well as levels of organics, toxic elements and POM. Solid fuel fired equipment, whether coal- or wood-fired, often does not permit extensive modifications of equipment or operating procedures to reduce NO_x levels. Investigative efforts in this area should continue to determine potential NO_x control technology while still concentrating on reducing the impact of other criteria and noncriteria pollutant emissions.

Cost data on NO_x control alternatives for residential heating systems was generally not precise. This prevented a detailed economic impact of widespread implementation of control alternatives. Future EA programs should deal in more detail with cost impact of NO_x control devices to achieve specific levels of control. However, presently available cost data indicate that the incremental cost of NO_x controls to the homeowner is often small (especially for new equipment) and generally reversable within a short time through savings in fuel oil consumptions.

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